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# Use of a Time-Shared Computer System To Control a Hall Effect Experiment

**U.S. DEPARTMENT OF COMMERCE  
NATIONAL BUREAU OF STANDARDS**

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## **Use of a Time-Shared Computer System To Control a Hall Effect Experiment**

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## ABSTRACT

An experimental time-shared computer system has been used to control and collect data from a Hall effect experiment. In addition to selection of the voltage sequence and control of specimen current and magnetic flux directions, the computer exerts positive control over the specimen temperature in accordance with a series of thermocouple voltages entered by the operator at the beginning of the run. The interface circuitry is constructed from four general purpose modules and a single special purpose unit. Details of the interface system and the programs used to control the experiment and to perform intermediate calculations are given. It was found that the time-shared system was well-suited to control an experiment of this type. The demands on the computer were essentially similar to those required by a human user interacting in a conversational mode. Substantial savings in time over manual data collection and reduction were realized; a temperature run with 38 to 40 data points between 10 and 320 K could be completed in less than 4 hours.

Key Words: computer-controlled experiment; data acquisition system; digital scanner; experiment-computer interface; Hall effect; system control module; teletypewriter interface; time-shared computer.

## 1. GENERAL INTRODUCTION

An experimental time-shared computer system has been used to control and collect data from an attached Hall effect experiment. Operation of the experiment together with its computer interface in a time-sharing environment has demonstrated that some types of experimental apparatus can be serviced on-line by a general-purpose time-shared system while that system is servicing a variety of other more typical users. This note, in addition to documenting a particular experiment, points out the characteristics of the experiment that make it amenable to time-shared operation. From these characteristics a class of experiments that can be practically assisted by a time-shared system may be identified.

Successful operation of an experiment in a time-shared computer environment requires that the experimental equipment place a low or moderate load on the computer system. In general, it is essential that the combination of experiment plus interface not require "critical real-time" service from the computer system. Critical real-time operation may be described as that in which the system must meet a strict upper limit in response time to service requests; this limit may require response within a few milliseconds or even a few microseconds.

Since most time-shared systems have attached teletypewriter or display terminals which interface individual users to the system and since these users can usually operate acceptably with a response time of a few seconds or more, most systems have been designed for this type of response, and in fact, the economics of their design depend on the acceptability of this response time. The actual response time of such multi-access systems is usually a few seconds, but may range from a few tenths of a second up to several seconds. This response is usually adequate for human users, and so the system is "real-time" with respect to their needs.

Since this type of response can be expected from most general-purpose time-shared systems, any interface to attached experimental apparatus must usually be designed to meet this constraint. The class of experiments referred to above is further restricted, then, to that which can benefit from on-line computer service with a response time of a few seconds or more.

The computational load of an experiment on an interface and associated computing equipment is variable. Some experiments may require a small computer or a large amount of special-purpose hardware adjacent to the experiment to satisfy their critical real-time response requirements. In some cases the small computer may provide all of the necessary computational capability. In other cases data logging can be done with either special-purpose hardware or a small computer using a machine-readable medium such as punched paper tape, punched cards, or magnetic tape. This data can then be used as input to a larger computer on a batch processing basis for analysis and summary.

In other cases, however, it is advantageous to have a larger computer system directly on-line with the experiment. This may be necessary because of a need for greater computational capability than is available with a small computer or special-purpose hardware. Such a large on-line computer can provide additional experimental flexibility with the power of more advanced languages and other software, faster computation, larger memory, and other features not available on a small computer. Depending on the nature of the experiment, it may be economically advantageous to be on-line with a larger computer system which is shared by several users, rather than to use a small computer solely for one or a few experiments.

The larger, usually remote, computer referred to above may service a number of experiments at one time or it may be only partially dedicated to servicing on-line experiments. If partially dedicated, its remaining capacity may be used to service general-purpose teletypewriter, display, or background batch processing users. The terms "small" and "large" computer as used above are relative, although there are identifiable classes of computer systems according to various measures, such as speed, instruction repertoire, and storage size. The amount of computing capability needed and the relative scales of computers in multi-computer configurations must be decided on an individual basis for each system.

The increasing availability of time-shared systems and the more generalized software which enables such systems to perform functions other than that of an advanced desk calculator, combined with several years experience in using small to medium-sized computers to control experimental equipment such as nuclear reactors and linear accelerators, has led to the application of such computer systems to more modest experiments [1].

This report discusses how a particular experiment was attached to a research-oriented time-shared system. It discusses factors influencing the load placed on the system, including pertinent attributes of the experiment itself and of the interface hardware. In addition, general comments from a user's point of view concerning the advantages and disadvantages of using automated logging and control devices for experimental equipment are included. The successful operation of this experimental configuration shows the feasibility of operating so-called general-purpose time-sharing systems in a dual mode---servicing experimenter and general terminal user at the same time.

## 2. USE OF A TIME-SHARED COMPUTER SYSTEM

### 2.1 The Time-Shared Concept

A large number of computer systems that have been implemented during the past several years have been labeled "time-sharing" systems [2]. Although these systems vary in capability, most of them have the general property of being able to serve a number of independent on-line users simultaneously. Some systems may limit user independence; however, all systems allow for apparent simultaneity of operation by multiple users. This is accomplished by time multiplexing various resources within the system. If use of such resources can be completed very quickly with respect to the response time expected by the individual users, then each user is given the illusion that he alone is using the system.

### 2.2 Response from Time-Shared Computer Systems

Interaction between a user and a time-shared computer system usually consists of a sequence of message pairs. Each pair consists of a message to the computer and a message from the computer. For example, the user types a string of characters on a teletypewriter keyboard and a response is received from the remote computer. This order of transmission may be reversed; a query from the computer may be followed by a reply from the user.

This strict pairing need not be maintained and implied groupings of transmissions in either direction may be used for specific interactions. Whether the interaction be user-directed or machine-directed, there is a lag within the computer system between the time a message is transmitted to it and the time a response is formulated. The "response time" may be defined as the period beginning with completion of transmission of the last character of a message to the computer and ending with receipt of the first character of the responding transmission to the user.

Response times of a few seconds are permissible for a human user who is interacting in a conversational mode. For some applications a response time of several seconds or even minutes may be adequate. Since the internal operating speed of most computers is a function of a basic cycle time which is of the order of microseconds, the response time for a simple response to a single user might be a fraction of a second. If, however, there are a number of users requiring service, and if some or all of these users require substantial computation or other time-consuming system activity, then typical response times will be considerably longer.

Experiments are usually connected to a computer system through intermediary interface hardware. A simple interface may consist of a buffer and a small amount of logic. The effective response time of the "computer system plus interface" is that which is of concern to the experimenter. Since a complex interface can make up for a slow computer response time in some cases, interface design depends on both the requirements of the experiment and computer capability. If only a few simple tasks require extremely fast response time and the rest can survive with longer response time but need substantial computation, then a very simple interface can provide the fast response time necessary for the critical tasks as well as provide interconnection to a computer system.

### 2.3 Shared Resources

A prime objective in operating a computer system in a time-shared mode is to share a common set of resources among several users. Economic gain for each user is possible providing that the users adhere to several limitations with respect to the available resources. These restrictions may be met quite easily for some applications, yet be hardships on others. By examining briefly those resources that are shared in a time-shared system the basis limitations on users become clear.

#### 2.3.1 Central Processor Units

A time-shared system contains one or more central processor units (CPU's). These are the basic modules for controlling the system and for performing arithmetic and logical operations. The capability of each CPU is fixed by its basic logic speed, number of internal registers, instruction repertoire, and basic organization. Some of this capability must be reserved for executive or bookkeeping functions within the system; that is, the dynamic allocation of system. The remainder of the CPU time is available for sharing among the various users.

The total demand for CPU usage by all users over any specified time period of a few seconds or longer must not be more than the time available on the CPU(s). Users requesting large amounts of CPU time are usually given low priority, so that system response time for such users is substantially longer than for highly interactive users.

Part of the basic justification for time-sharing is that users need substantial computing capability for very short periods, but that these needs arise only occasionally. For example, a user may require 50 ms of CPU time and then not again request service for several seconds until the computer's response has been typed out and the user's next message formulated and typed into the system. It is possible that when any one user requests CPU time no other user may have an active request pending. It is likely, however, that the user's program must wait in a "queue" for its slice of CPU time. Successful operation of time-sharing systems depends on successful estimates of the probability of usage of each of the resources by the various users. Elementary queuing theory can be applied to estimate loads in various parts of time-sharing systems based on predicted user behavior.

#### 2.3.2 Storage

Another resource shared in a time-shared system is storage. Main storage, usually core memory, is very expensive relative to other parts of the system. Usually not enough is available to allow a program associated with each user to remain in core all of the time. It is necessary to swap programs or parts of programs in and out of main core before and after they use their share of CPU time. Backup memory, drum or disc, is used to store active user programs when they are not in core memory. It is obvious that the less core a given user requires for an application, the less burden he is placing on the expensive core memory resource within the system.

Backup memory--drum, disc, or magnetic tape--is also shared. A large amount of such memory is usually available, but since there must be some limit even to this amount of backup storage, restrictions are usually placed on the number of files each user may store.

#### 2.3.3 Communications

The communication link between users and the computer system is another important resource. The design of the interface between computer system and remote terminals must ensure that no data be lost when communicating at normal data rates. It is necessary to provide a limited amount of hardware for each communication line, since queues cannot be held in a simple remote terminal which has no buffers. Because the servicing of communications lines requires either CPU or the action of a special-purpose controller, each user is restricted in frequency and size of messages. A basic restriction may be to limit him to the capacity of a single telephone line.

Because of the expense of communications lines and equipment and because individual lines are quite likely not shared as are resources within the time-shared system itself, it is economically advantageous for individual users to use the minimal communication facilities necessary for their applications.

## 2.4 Configurations Using Time-Shared Systems

A variety of configurations are possible for interconnecting experimental apparatus to a time-shared computer system. Three examples of such configurations are described below, and one can incorporate any combination of these in a system designed to service a specific set of applications.

(a) An experiment may be connected via a specially designed hardware interface to a time-shared system that services this and a few other specially interfaced experiments. An example of this configuration is the use of a small computer to monitor several experiments connected to a nuclear reactor, providing service on-line to a number of experimenters simultaneously.

(b) An experiment can be connected via a special-purpose hardware interface to a large general-purpose time-shared computer system. The hardware interface can be designed such that the burden on the time-shared system is of the same order as that placed on the system by more usual teletypewriter or display terminals. The experiment described in this report is an example of this configuration.

(c) An experiment can be connected to a small computer which itself is connected as a remote terminal to a larger time-shared computer. An experiment which requires servicing of a number of critical real-time needs, yet requires substantial computation available on-line but with no such critical response time, is a candidate for this type of configuration.

## 3. THE HALL EFFECT EXPERIMENT

### 3.1 The Effect

The Hall effect is widely employed in the characterization of metals, semiconductors, and insulators. Its importance arises because of the direct relationship between Hall coefficient and free charge carrier density in a solid. If electric currents are carried dominantly by one charge carrier, the Hall coefficient,  $R_H$ , is given by

$$R_H = \frac{r}{nq} \quad (3.1)$$

where  $n$  is the free charge carrier density, and  $q$  is the charge of the carrier. The proportionality factor,  $r$ , which is of the order of unity, depends on details of the energy band structure of the solid, the scattering mechanisms, temperature, magnetic flux density, and current and flux directions.

Use of the Hall effect in the study of semiconductor crystals [3, 4] has been particularly significant since the charge carrier density in these materials depends on the density and kinds of impurities in the crystal. Additional information concerning carrier transport can be obtained if the Hall coefficient is combined with the resistivity. In the one carrier case the Hall mobility,  $\mu_H$ , is the ratio:

$$\mu_H = \frac{|R_H|}{\rho} \quad (3.2)$$

where  $\rho$  is the resistivity measured at zero magnetic flux density, and  $R_H$  is measured in the low flux density limit.

The Hall effect results from the combined action of electric and magnetic fields on the free carriers in a solid. In the most usual case, mutually perpendicular electric and magnetic fields are impressed on a solid, and the charge carriers are deflected in the third mutually perpendicular direction. If the current distribution is constrained to remain unchanged when the magnetic flux is applied, as for example in a long, bar-shaped specimen, a transverse potential difference, called the Hall voltage, is developed to oppose the deflection of the charge carriers as a result of the build-up of deflected carriers at the edges of the specimen. The Hall coefficient is the ratio of the transverse electric field due to the Hall voltage to the product of the current density and magnetic flux density:

$$R_H = \frac{E_y}{J_x B_z} \quad ,$$

where  $J_x$  is the current density along the length of the bar (the  $x$  direction),  $B_z$  is the magnetic flux density (in the  $z$  direction) and  $E_y$  is the Hall field (in the  $y$  direction). The sign convention for the Hall effect is shown in Fig. 1. As expected from Eq. (3.1) the sign for  $p$ -type semiconductors, in which the carriers are positively charged "holes,"

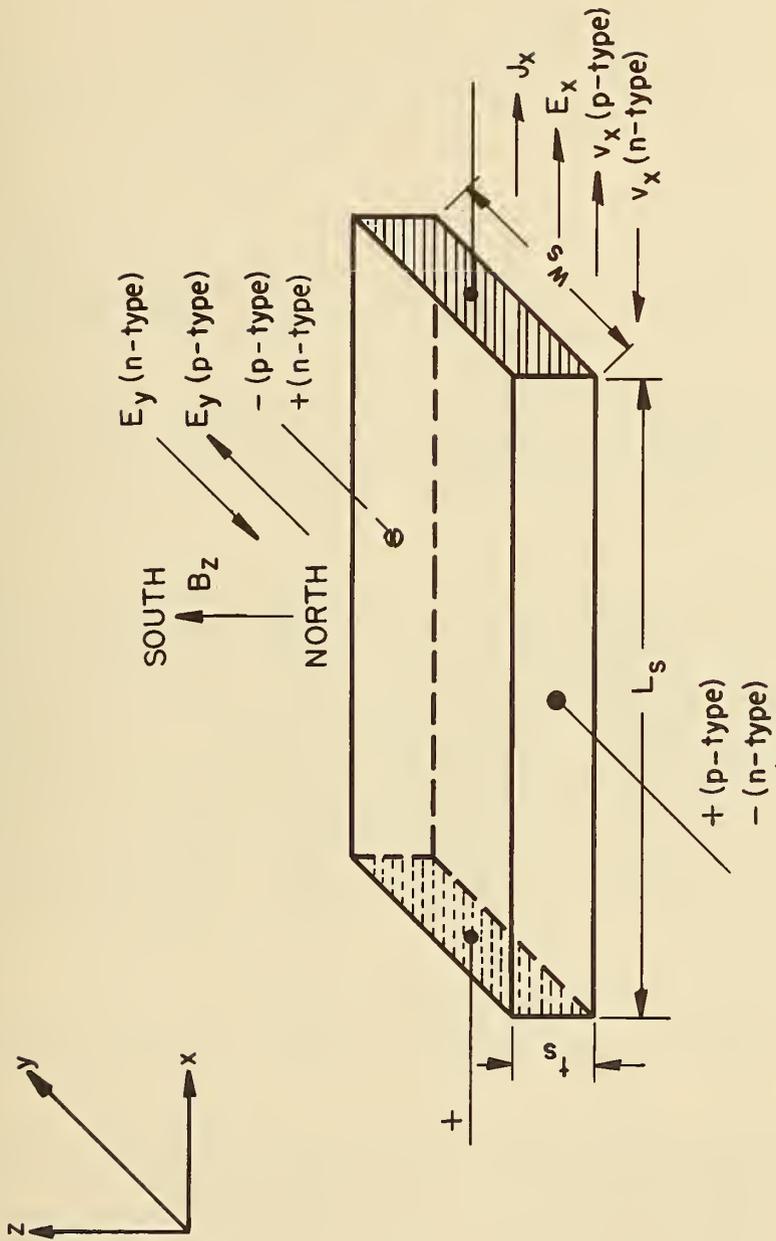


Figure 1. Hall effect sign convention. With an electric field applied in the x-direction and magnetic flux density in the z-direction, the Hall field appears in the y-direction.

is positive while for n-type semiconductors, in which the carriers are negatively charged "electrons," it is negative.

Many different specimen shapes can be used for Hall measurements [5]. Specimens used in this experiment were ultrasonically machined bars of germanium or indium antimonide. The specimens had two side arms on each side and enlarged end contacts as shown in Fig. 2. The geometry of these specimens conforms to the ASTM standard [5]. In this configuration, one can measure two Hall voltages (between arms 3 and 4 or between arms 5 and 6 and two resistivity voltages (between arms 3 and 5 or between arms 4 and 6). In order to minimize the contribution from misalignment and thermomagnetic effects, it is necessary to measure the Hall voltages for both directions of current and magnetic flux [6] and take a suitable average. It is also customary to measure the resistivity voltage with no magnetic field for both directions of current.

At the minimum, the complete sequence of measurements includes the following: B(+), I(+,+), V34(+,+), V56(+,+), I(+,-), V34(+,-), V56(+,-), B(-), I(-,+), V34(-,+), V56(-,+), I(-,-), V34(-,-), V56(-,-), B(0), I(0,+), V35(0,+), V46(0,+), I(0,-), V35(0,-), and V46(0,-). In these expressions, the first symbol in the parenthesis represents the condition of the magnetic field; the second represents the condition of the current.\*

Measurements of Hall coefficient at a single point are frequently used in routine determinations of carrier density in order to deduce the impurity density in the crystal. However, much more information can be obtained if the Hall coefficient is determined as a function of some variable such as temperature or magnetic flux density. The independent variable in these experiments was the specimen temperature; the magnetic flux density was fixed.

### 3.2 Apparatus

The contact areas of the Hall bar were tinned with indium-tin solder. Small diameter wires were attached to the soldered regions for later use in connecting the specimen to the electrical terminals in the holder. Fig. 3 shows the various parts of the specimen holder. The Hall bar was soldered to a small copper block which in turn was secured to the holder. The bar was electrically insulated from the copper holder by a 0.5 mm thick sapphire plate which provided good thermal contact. A copper cover completed the enclosure for the specimen. An outer cylinder, with a 500- $\Omega$  heater of manganin wire wrapped around it, surrounded the enclosure. The specimen holder was connected by a long piece of thin-wall, stainless-steel tubing to a header through which passed the electrical leads and thermocouples. This assembly was lowered from above into the double glass Dewar system shown in Fig. 4. The header mated with the stainless-steel fittings above the inner Dewar flask to complete an enclosure which could be evacuated. The tail of the Dewar system was centered in the gap of an electromagnet with 6-in. diameter pole faces. The holder was positioned so that the magnetic flux was perpendicular to the two flat faces of the specimen.

Usually measurements were made with a flux density of 0.6 T, but it was variable up to a maximum of 0.67 T with a 2.5-in. gap between the pole faces. A commercial Hall generator was mounted on one of the pole faces, and its Hall voltage, calibrated against a nuclear magnetic resonance fluxmeter, was used to determine the value of the magnetic flux density.

The current through the magnet coils must be turned on and off and reversed during the data collection. These changes were initiated by relay closures supplied by the command decoder discussed in Section 5.8. These closures complete the circuit for the 110-V relay coils which turned the magnet current on and off. The magnetic field was reversed by first turning the current off, then reversing the contacts for the magnet current using a two-coil, latching-type relay, and finally turning the current on. A time-delay relay prevented the current from coming on during the 5 s required for the reversing procedure.

A combination of heating and cooling was used to raise the specimen holder to any desired temperature above that of the coolant. The liquid level was below the holder and its normal boiling provided a steady efflux of cold gas which cooled the holder. The computer-operated temperature control circuit supplied sufficient power to the heater to increase the

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\*It will be convenient later to replace these symbols with subscripts as listed in Table 3.

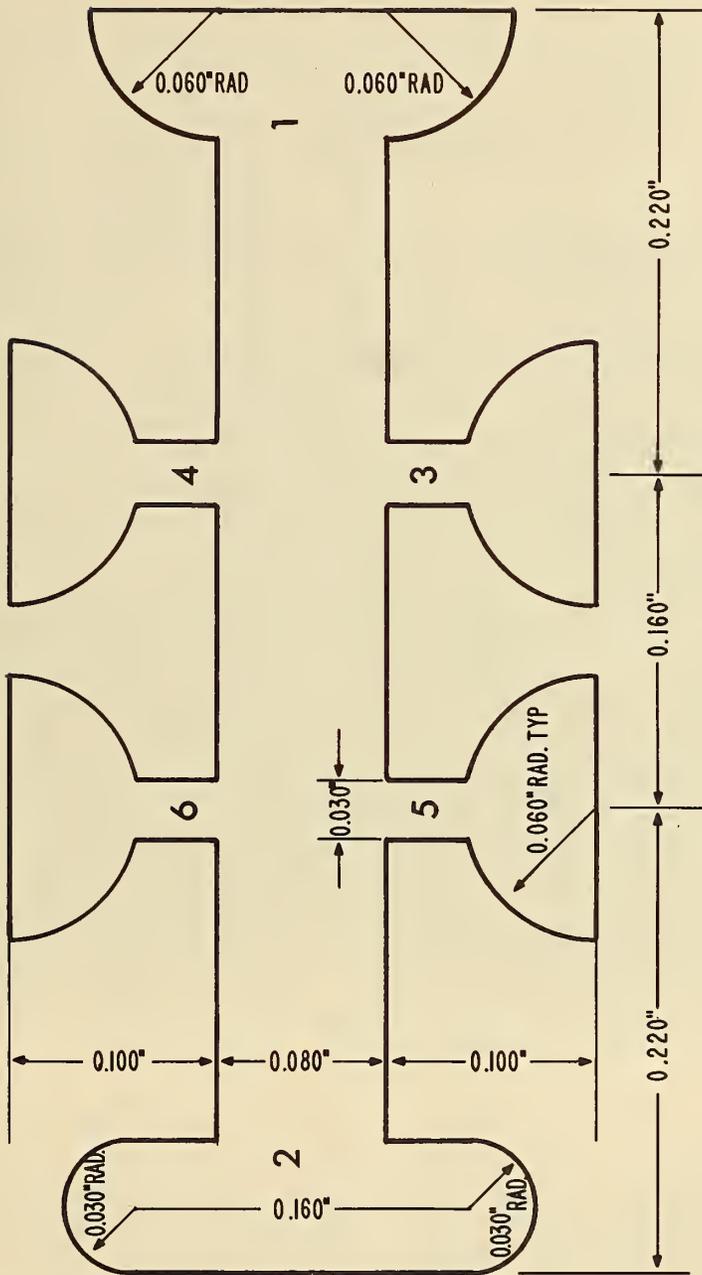


Figure 2. Hall specimen geometry.

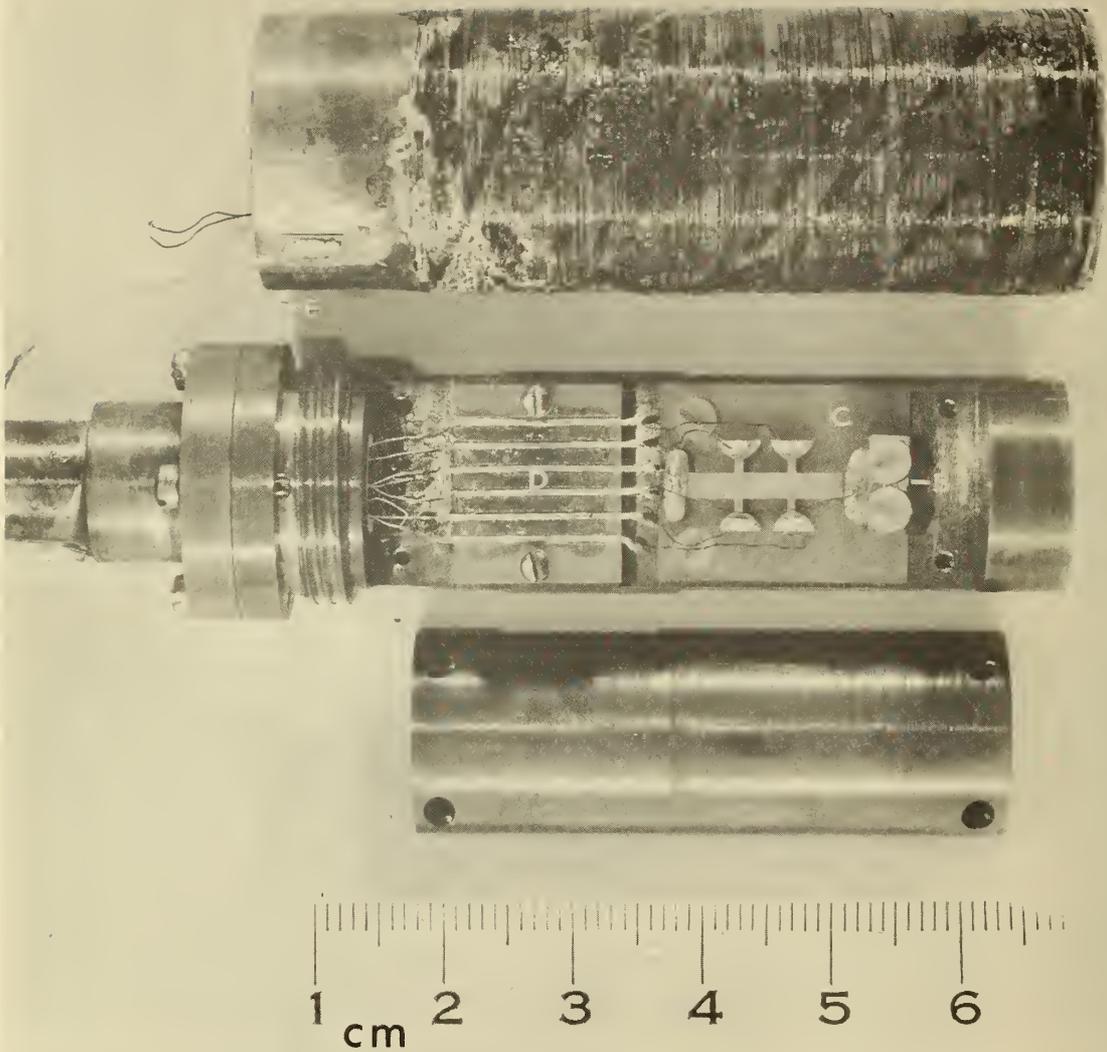


Figure 3. Specimen holder. Hall specimen (A) was soldered to copper block (B) and secured to holder with sapphire plate (C) providing electrical insulation. Lead wires from each arm of the specimen were attached to respective pins (D) for electrical connection to measurement circuit. Cover (at bottom) was placed over specimen, and cylindrical jacket (at top) with heater windings completed the assembly. Outside thermocouple (E) was attached to metallized ceramic plate (F) on jacket.

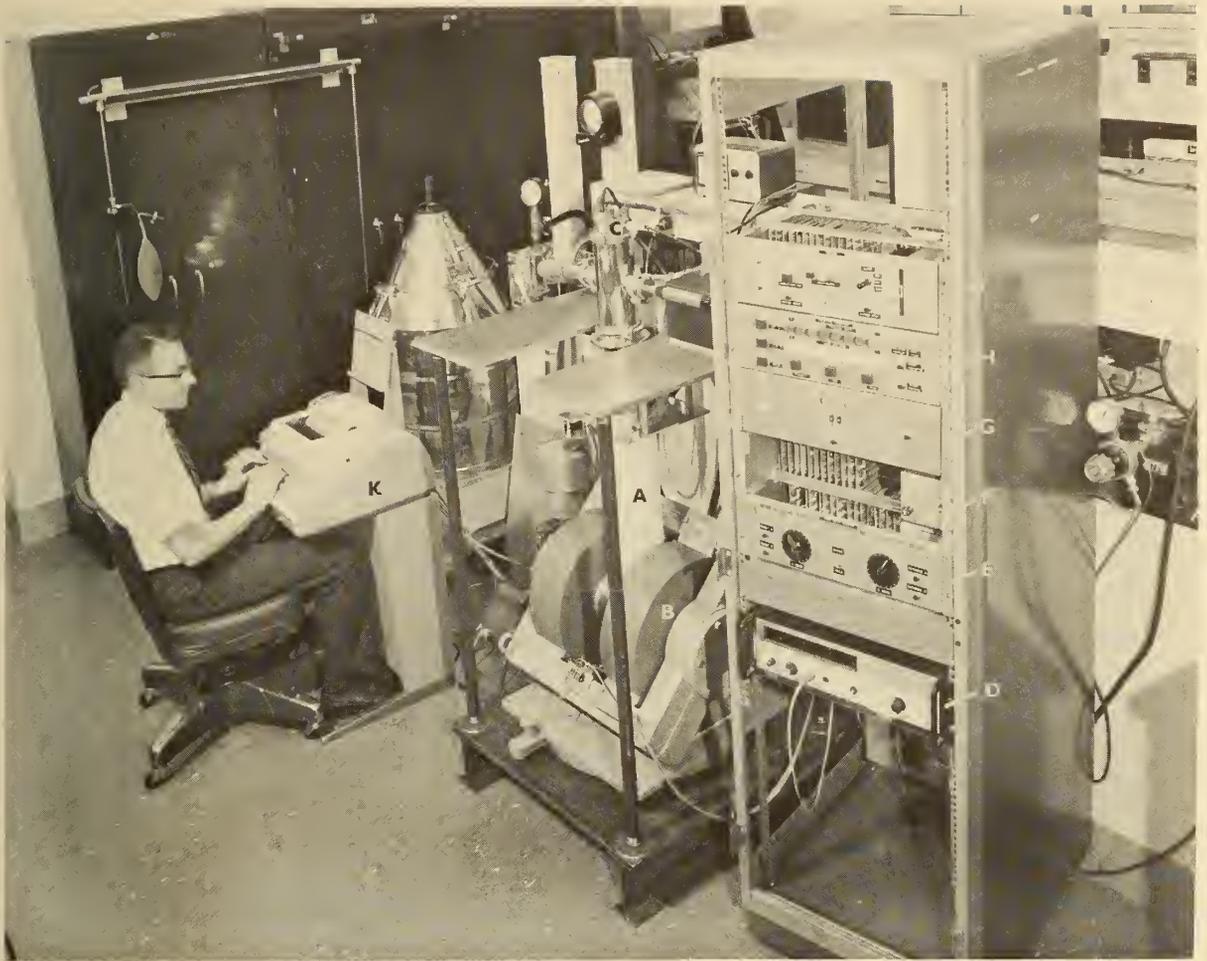


Figure 4. Hall effect experiment with attached computer interface. Double Dewar flask (A) was supported between poles of 6-inch electromagnet (B). Connections between the specimen holder assembly and the external circuitry were made at the header (C). Equipment rack contained digital voltmeter (D), reed relay scanner (E), special interface module (F), digital scanner (G), teletypewriter interface (H), and control module (J). Operator communicated with experiment through teletypewriter (K).

temperature of the holder quickly until the desired temperature was reached. Then the heater current was reduced to that needed to balance the cooling effect of the cold gas flowing past the holder. The control circuit compensated for slight variations in the cooling rate which occurred during a run as the liquid level fell in the Dewar flask, and from run to run as the flask "softened." A flask goes "soft" because helium gas diffuses through glass and reduces the vacuum between the walls of the flask. This results in increased heat transfer from the outside to the inside wall and a corresponding increase in the boiling rate of the coolant.

The normal evaporation of the liquid provided some cooling which corrected for slight overshoot in the heating. For more cooling it was possible to reduce the pressure over the liquid but it was found that a steady cooling rate was difficult to maintain by pumping, so it was seldom done. However, if it is desired to lower the temperature of the sample quickly, pumping is helpful as the cooling rate of the normally boiling liquid is fairly slow. Also, blowing warm gas down the transfer line into the cryogenic liquid in order to increase its boiling rate was found to enhance greatly the cooling rate. Passing current through a small resistor in the bottom of the inner Dewar flask would serve the same purpose.

The mass of the specimen holder was sufficient for good temperature stability, but small enough so it could change from one temperature to the next fairly rapidly. One thermocouple was placed in the main part of the holder near the specimen and another was placed on the outside cylinder just above the heater windings. Because the holder was composed of several parts with the heater on the outside, the inside thermocouple was slightly behind the outside one in its response to the applied heat. The power was controlled to keep the outside thermocouple at the desired temperature and allow the inside one to come into equilibrium with it.

Gold (with 2.1 atomic percent cobalt)-chromel thermocouples were used to determine the temperature. The sensitivity is 11  $\mu\text{V/K}$  at 10 K and increases to 50  $\mu\text{V/K}$  at 100 K [7]. A thermocouple from the same wire was calibrated by the NBS Temperature Section. Frequent calibration checks at 4.2 and 77 K were made on the thermocouples in the system as it is known that the gold-cobalt is not a stable thermocouple element [8]. Gold-iron compositions are more stable and more sensitive than gold-cobalt below 20 K, but unfortunately the output of the gold-iron wire changes in a magnetic field [9]. A germanium or carbon resistance thermometer is a more appropriate temperature sensor below 10 K.

The electrical circuit used to measure the Hall and resistivity voltages is shown in Fig. 5. The current source was a regulated power supply. The current through the specimen was determined from a measurement of the voltage across a standard resistor which was variable in decade steps from 1 to  $10^{10}$   $\Omega$ . Selection was made by means of a manual rotary switch.

### 3.3 Adaptability to a Time-Sharing Environment

The relationships between Hall coefficient or resistivity and temperature are complex functions which have many inflection points. The greatest amount of information can be deduced from experimental data if the points are taken sufficiently close together that the curves can be accurately determined. Because of the large number of measurements which must be made at each temperature, the number of data points which can be taken during a run is severely limited if the data are collected by hand. It is in this application that computer control of the experiment is most valuable because both the time between points and the time required to obtain the data can be significantly reduced.

The time involved in the operation of the Hall experiment are long compared with the cycle time of the computer. For example, temperature need be sampled only every few seconds even during the time when the computer is controlling the changing of temperature from one stop point to the next. In changing magnetic field, delays of 10 s or more are required to permit the field to stabilize. A set of data is collected only every 5 to 10 min so detailed computations are required only at infrequent intervals. Hence, this experiment is an ideal candidate for use on a time-shared computer system.

Although the interest in the present experiment was restricted to Hall effect and resistivity as a function of temperature, extension to determine other galvanomagnetic and thermomagnetic effects would have been a simple and straightforward matter since all involve

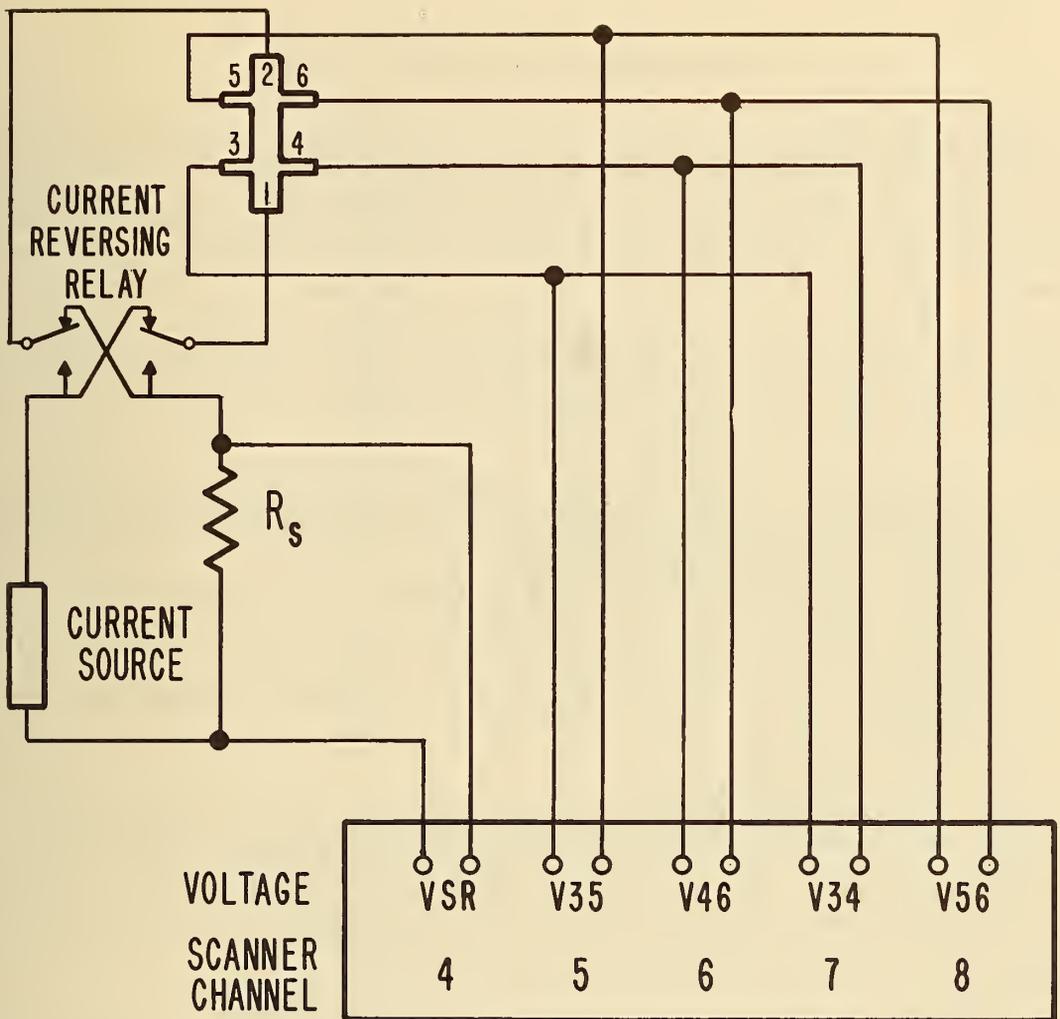


Figure 5. Electrical circuit for measuring specimen voltages.

the measurement of voltages, either directly on the specimen as in the Hall effect or as the output of thermocouples as in the Seebeck or Nernst effects [3].

#### 4. THE EXPERIMENT/COMPUTER CONFIGURATION

##### 4.1 Over-all Configuration

The Hall-effect experiment together with its associated hardware interface was connected to the NBS CORD (Computer with On-line Remote Devices) Time-Sharing System using a teletypewriter-rate communication line. The experiment was designed to interface to the time-sharing system in a manner identical to more conventional remote terminals. Communication, CPU, and memory requirements do not exceed that normally encountered with usual teletypewriter operation.

Figure 6 shows the over-all experiment/computer system configuration. The interface, switch-box, teletypewriter and experiment shown in Fig. 4 are located on another floor and approximately 30 meters from the computer system. Interconnection is made with a two-wire shielded cable which allows full duplex communication between the experiment and the communications controller of the time-sharing system.

The switch box provides for either local or computer-controlled operation. When in local mode, everything typed on the teletypewriter is transmitted to the interface and control characters from the computer may be simulated. Output from the interface is printed on the teletypewriter. In computer-controlled mode:

- a. Everything typed on the teletypewriter is transmitted to the experiment interface and to the computer.
- b. All computer output is both transmitted to the experiment and printed on the teletypewriter.
- c. All experiment output is both transmitted to the computer and printed on the teletypewriter.

##### 4.2 The Time-Shared Computer System

The NBS CORD Time-sharing System is designed to serve a limited number of remote devices such as teletypes, display consoles, a flying spot scanner, and special experiments. The system is built on the MOBIDIC B dual computer system, which has been modified to meet NBS time-sharing requirements. The two computers within the system have specific functions, the executive for system control and the user for executing programs associated with remote terminal users. Core memory of the user computer is partitioned among the users active at any given time and also includes a small supervisory program.

Figure 7 shows the connection of the experiment to the computer system via the communications controller. The controller, also shown at the right in Fig. 8 is a manually switched device that allows interconnection of combinations of remote terminals with the executive processor. This processor is responsible for communication with all remote devices, control of the user processor, and access to backup memory.

Magnetic tape has been the primary backup memory; however, disc has now been added along with a completely revised system for file storage. Storage for the Hall-effect experiment has been on magnetic tape, both for programs and data.

A general set of system commands is available to teletypewriter users for program loading and execution as well as for file manipulation. Several language processors are constructed as subsystems within the general system framework. These include an assembler, CAS (CORD Assembler), a compiler (similar to BASIC), and a list processing system, CL6 (a conversational system based on Bell Laboratories Low Level Linked List Language). All subsystems interact with terminal users.

Programming for the Hall-effect experiment was done in CAS Assembly Language and program execution is controlled by the use of system commands at the teletypewriter associated with the experiment.

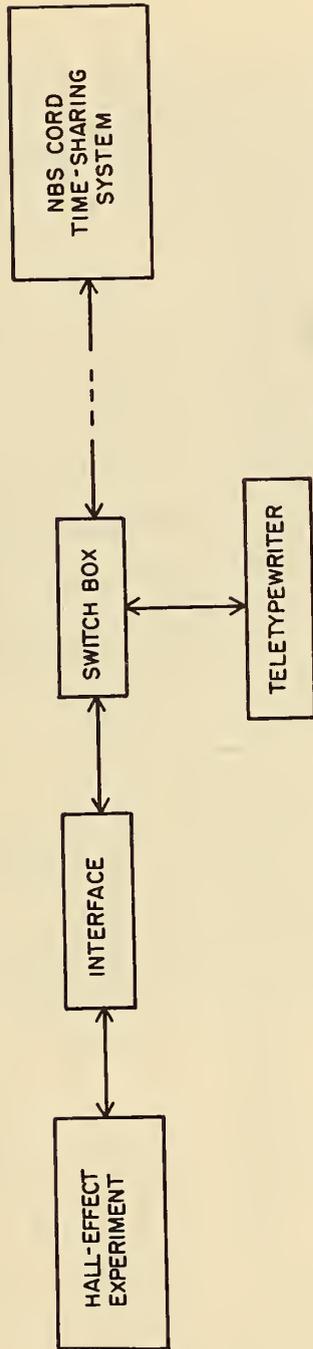


Figure 6. EXPERIMENT / COMPUTER CONFIGURATION

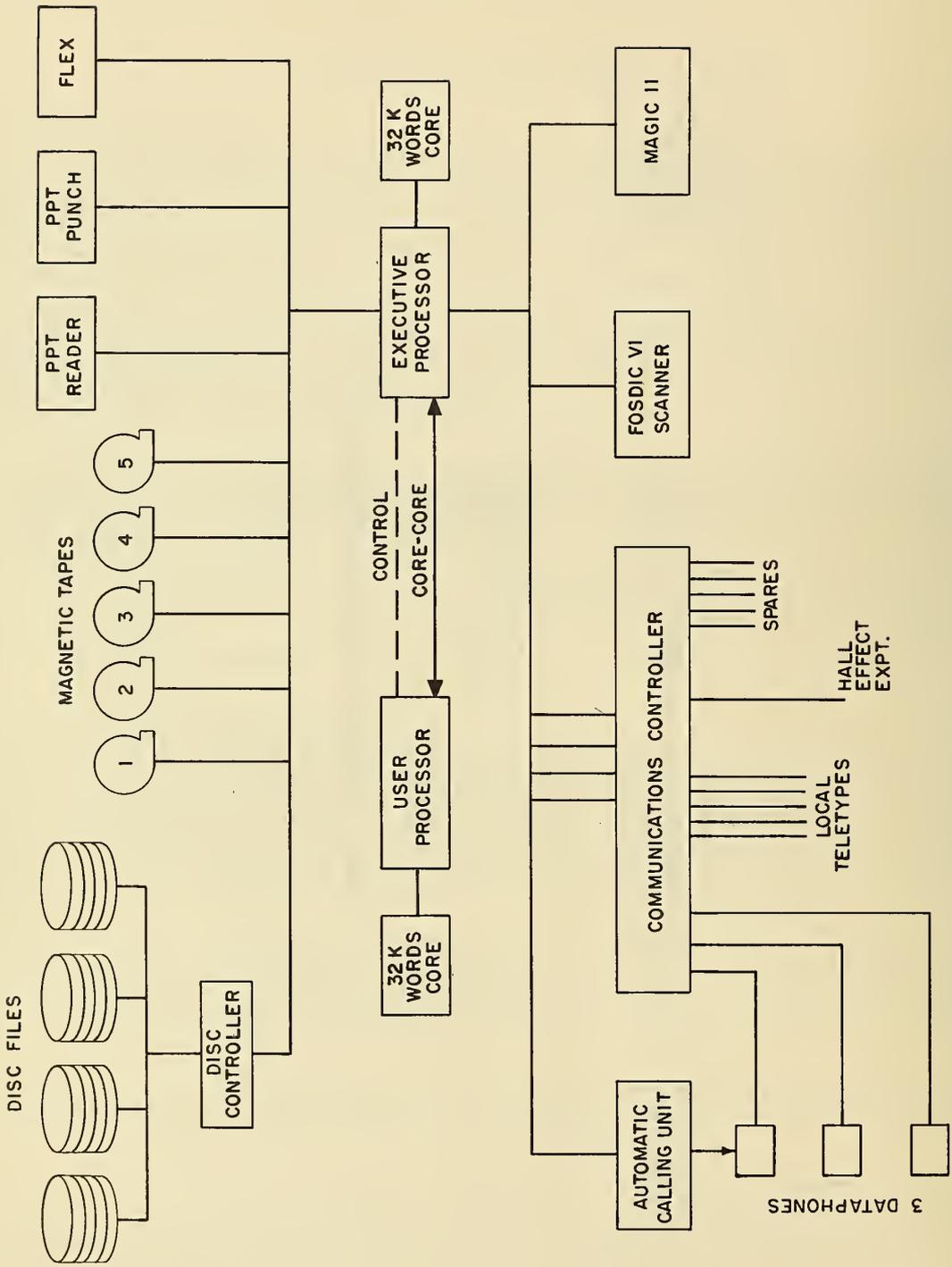


Figure 7. Block diagram of NBS computer research facility

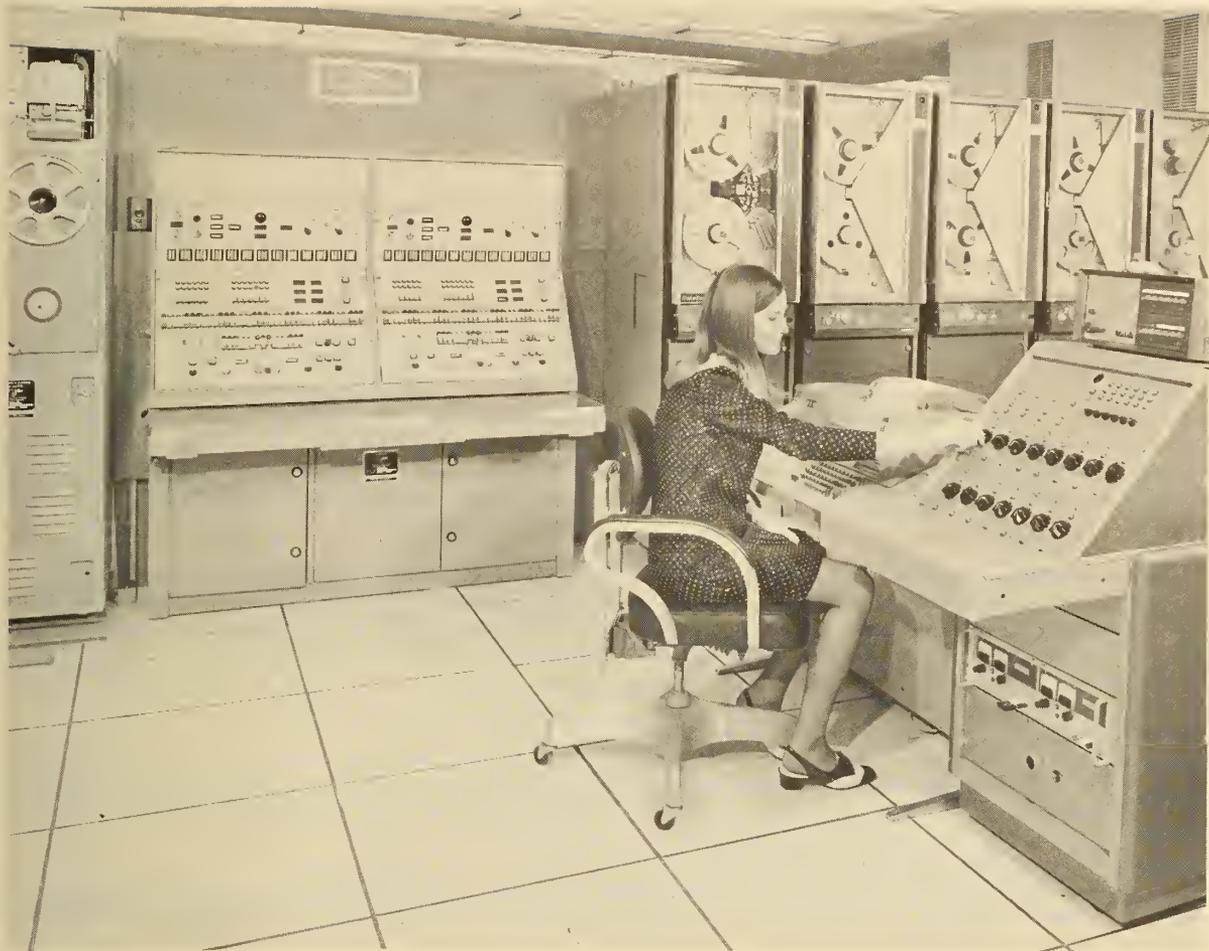


Figure 8. NBS CORD time-shared computer system

## 5. THE HARDWARE INTERFACE

### 5.1 Measurements Automation Modules

The hardware interface between the Hall effect experiment and the time-shared computer system has been constructed utilizing a set of general modules for data logging and computer interfacing. These modules are engineered for flexible interconnection and operate under the asynchronous control of a supervisory module equipped with a patch board for input of the control program. Each module is constructed with pluggable printed circuit cards and contains its own power supply, indicator lights, manual controls, and standard connectors for both control and data signals. This permits the convenient assembly of systems tailored to the particular requirements of individual applications such as the Hall effect experiment.

### 5.2 Configuration of the Modules

The interface consists of four general purpose modules, one special purpose module, and a commercial digital voltmeter. Figure 9 indicates how these modules are interconnected and shows their relative position in the system.

All parameters and variables that need to be measured are available from the Hall effect experiment as d-c voltages. This makes it possible to take all measurements with a single instrument, an auto-ranging digital voltmeter. The voltmeter is connected to the experiment through a reed-relay scanner module. The output from the digital voltmeter is converted to a bit-serial signal so that the data can be transmitted to the computer in teletypewriter-compatible form. This conversion is accomplished in two steps. The digital scanner takes the parallel data word from the voltmeter and converts it to a serial string of characters; then the teletypewriter interface module converts each character to a serial string of bits.

The hardware needed to decode control commands from the computer is contained in an interface module designed for the Hall effect experiment. Single-character codes sent by the computer can start one of two preset scanning and digitizing sequences. Once a scan code is received, the control module assumes its supervisory role; checking status signals and issuing commands to the rest of the modules until all the voltage readings have been transmitted to the computer.

Control of the magnetic field in the experiment (on, off, forward, reverse) is also accomplished by single-character codes from the computer. In this case the control module is not involved since the interface module serves directly as the command decoder and relay driver.

The special interface module also decodes computer commands for control of specimen temperature. Two methods of temperature control have been used. The first employed a single-character code to indicate a heater current pulse; the pulse duration and magnitude of current were preset manually. Experience with the system showed that this method was inadequate so another method was developed in which current is supplied continuously to the heater but the computer adjusts the magnitude of this current. This method requires two code characters. The first character indicates that the next character is to be processed as a heater current value. The second character is then switched to a digital-to-analog converter which in turn drives a programmable power supply that supplies current to the heater.

### 5.3 Reed Relay Scanner Module

The reed relay scanner module is a sequential multiplexing device which can scan up to twenty separate analog data channels and connect them to a common output line. The multiplexing is done through double-pole, single-throw, normally-open reed relays. The twenty channels are arranged such that they can be separated into two independent groups which are designated SCAN A and SCAN B, both of which are under the direction of the control program. The length of either cycle is continuously adjustable by means of selector switches, but the combined length of both is limited to the 20 input capacity of the scanner. Scan cycle A always begins at input 1, and ends at the input selected by switch A. Scan cycle B always begins at input adjacent to the end of Cycle A and ends at the input selected by switch B. The scanner will go to an error state and halt if switch B is set to an input which is within scan cycle A.

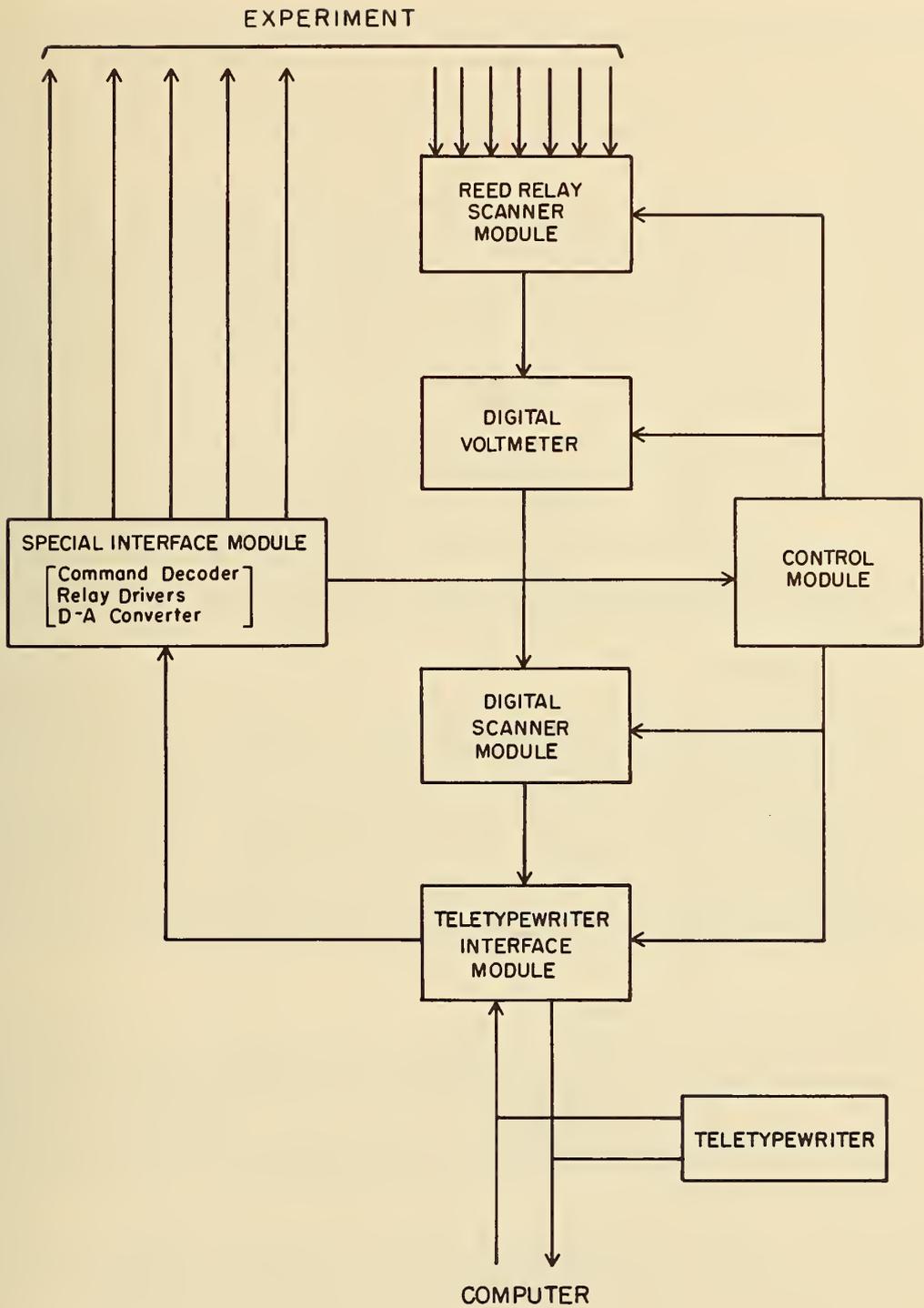


Figure 9. INTERFACE BLOCK DIAGRAM

Each of the scan cycles is controlled by two commands: RESET SCAN, which readies the scanner to sample the first input of the cycle, and ADVANCE SCAN, which connects the digital voltmeter to the next input signal, initiates a "convert" command to the voltmeter and readies the scanner to sample the next input. If the next sequential input is outside the preset limits, the scanner returns to the first input of the cycle. The ADVANCE SCAN command for cycles A and B can be the same signal, in which case the currently employed scan cycle advances.

#### 5.4 Digital Voltmeter

The digital voltmeter is a commercially available unit in which measurements are made by a dual-slope integration technique which minimizes the effects of long term drift in component values in the measuring circuits. Manufacturer's rated accuracy is  $\pm 0.01$  percent of reading  $\pm 2$  digits. Voltage ranges of  $\pm 0.1$ , 1.0, 10, 100 and 1000 V full scale are selected automatically, manually, or by remote control. Measurement time is 250 ms on all ranges or 50 ms on the four high ranges, depending on the setting of a rear panel switch. These measurement times do not include the time required for range changing in the automatic mode which, in the worst case, is 2.2 s.

The digitizing is done with four full decades plus a fifth digit to allow a maximum reading of 16 000 on all ranges. Parallel readout in 8-4-2-1 BCD code is provided at rear panel connector. Included in the readout is an indication of polarity and decimal point location.

The conversion cycle can be triggered internally at a rate governed by a front panel control or externally by a command pulse. When the conversion cycle is in progress, a control signal indicates that the unit is busy; when the cycle is complete, a "print" pulse is generated.

#### 5.5 Digital Scanner Module

The digital scanner module is a multiplexing device for connecting parallel digital data sources to serial-by character output devices. It can switch sequentially up to sixteen inputs of eight lines, each to a common set of eight output lines. The switching is done by solid-state digital circuitry built from an NBS family of circuit cards [10].

The scan cycle is always sequential but its beginning and end points can be selected by front panel switches to any of the channel numbers, 0 through 15. If the channel number for the start of the cycle is higher than the end number, the scanner will advance to channel 15, back to 0, then on to the end point. The scanner will continuously select one channel if "Start" and "End" are set to the same number. The scanner is controlled by two commands: SCAN, which sets the scanner to the "Start" channel, and ADVANCE, which steps the scanner to the next channel in the sequence.

#### 5.6 Teletypewriter Interface Module

The system described in this report uses an eight-bit code for each character. The maximum transmission rate between the experiment and the computer is ten characters per second. The signal that is transmitted and received is a serial stream of eleven bits for each character: eight data bits preceded by a start bit and followed by two stop bits. Characters may be sent to the teletypewriter asynchronously at any rate up to the maximum of 10 per second but the timing of the bits within the character is fixed and must be carefully controlled. However, machines with different transmission rates can be accommodated by the interface module.

The signals described above differ considerably from those of most other digital instruments and devices used in system instrumentation. The latter typically generate data with four bits per character and the bits are made available simultaneously on parallel lines. The conversion of the parallel lines data to serial form is the primary function of the teletypewriter interface module.

Code conversion is another requirement for the interface. Generally the parallel data is binary-coded decimal (BCD), while the teletypewriter accepts only the USA Standard Code for Information Interchange (USASCII). This module can convert any four-line code (sixteen characters maximum) to a subset of the USASCII code.

The module may be connected to the serial data line in much the same way as the teletypewriter is connected, i.e., half duplex (send and receive units in series) or full duplex (separate lines for send and receive). A current of 20 mA for the signal line is supplied by the module.

The module has an eight-bit (one character) buffer register which is essential to both input and output operations. A LOAD command pulse causes parallel-line data which has passed through the code conversion network to be loaded into the register. The loading operation is followed automatically by a serializing operation which puts the code on the serial line. Incoming signals appearing on the serial data line are loaded into the buffer register by a shifting operation. The contents of the register are retained until a new character appears on the line or until another output command is executed. For test purposes, the register may be loaded manually by front panel pushbuttons. A TRANSMIT command initiates the serializing operation without loading new data into the register.

When using a teletypewriter as a data recording device it is usually necessary to insert certain format control characters into the data in order to obtain a readable copy on the printer. For this reason, provisions are made for forcing codes into the data register without going through the normal data inputs. Three codes may be transmitted this way and the code transmission is initiated by command pulses. One of the command inputs will give two characters in succession, CARRIAGE RETURN and LINE FEED. Another command will produce LINE FEED only and a third will produce a SPACE. Other codes may be used in place of those given above; coding is done with a patch panel on the rear of the module.

Paper tape readers are included as a part of many teletypewriters, and in some systems it is necessary to be able to start and stop the reader by remote control. The interface module provides for this control in two ways: either one character will be read when a READ command pulse is received or a START READ command may be used to cause the reader to run until a STOP READ command is received.

The interface module generates a variety of busy signals to inform the system controller of its status. Termination of these signals is used to initiate each new action by the system controller. MECHANICAL BUSY is a negative level that is present for 0.1 s, starting when a character begins to be serialized out or in; this could be the result of a LOAD, TRANSMIT, READ, or special format command or the start of a signal coming in on the serial line. REGISTER BUSY will begin at the same time as MECHANICAL BUSY but will end as soon as the buffer register is quiescent which will be at least 18 ms prior to the end of the inception of a LOAD Command or one of the special format character commands until the loading of the register has been accomplished. READ BUSY is a negative level present from the inception of a READ or START READ command until the required reading has been accomplished.

## 5.7 Control Module

The control module exercises supervisory control over the other interface modules. Depending on the status of the system, as indicated by signals on the condition lines (busy signals, time signals, switch positions), the control module generates "do" commands to the other modules in the system.

The actions of the control module are governed by a program which can be stored wither on a plugboard or on matrix cards which can be inserted in the control module card cage. The plugboard is employed when frequent changes in the control program are expected, such as during initial programming. The fact that the plugboard is easily changed can also become a handicap since it means that the program can be inadvertently changed. Therefore, as soon as the program is debugged, it is transferred to matrix cards.

The control module performs an instruction every 50  $\mu$ s. The instruction is:  
Energize indicated "output lines" (the "do" command);  
Test, simultaneously, the selected conditions; and  
Go to Next Step as determined by the state of the selected conditions.

The program specifies two "next steps"; the control goes to one when the selected conditions are met, and to the other when the selected conditions are not met.

The control module has a capacity for sixteen instructions, eight commands, and fourteen condition lines.

Also available in the control module are various control elements, including three J-K flip-flops, two adjustable one-shots, and an adjustable-RADIX, four-bit counter.

### 5.8 Special Interface Module

The modules described above are all general purpose modules, that were designed without a particular system in mind but with sufficient flexibility to allow their use in many data gathering systems. Nearly every system has its own unique requirements. These requirements for the Hall effect experiment are handled by the special interface module.

One major function contained within this module is impedance matching and voltage level shifting required for the digital voltmeter. Another function is that of command decoding of characters received on the teletypewriter line from the computer. Decoding is done by a diode matrix whose inputs are connected to the outputs of the buffer register in the teletypewriter interface module. The outputs of the decoder are used to drive relays, signal the system control module, or initiate other control sequences in the interface module. The following is a summary of the USAScii codes which are decoded, their function and the method used to accomplish the function:

- " (Quotation Mark) Magnetic Field On/Off. The decoder output line drives a relay that energizes switches which control the magnetic field.
- ! (Exclamation Point) Magnetic Field Direction. This function is accomplished in the same manner as Magnetic Field On/Off.
- # (Number Sign) Pulse Heater. The decoder output line drives a DPDT relay via a monostable multivibrator with an adjustable run time. Current may be supplied to the heater through the relay contacts.
- ( (Left Parenthesis) Heat Code Coming. This decoder output arms control circuits so that the next character received over the teletypewriter line will be stored and gated to a digital-to-analog converter. The resulting analog voltage is used to control a programmable power supply which supplies current to the heater.
- \$ (Dollar Sign) Read All Data. This decoder output is connected to the system control module to cause the controller to initiate a SCAN A sequence. This causes all data channels to be sampled.
- % (Percent Sign) Read Temperature Only. This causes the controller to initiate a SCAN B sequence which reads only the two temperature channels.

All control characters sent by the computer to the interface are printing characters so that they may be observed on the teletypewriter print-out. Teletypewriter output contains a complete record of all transmissions to and from the experiment as well as the results of calculations of each stop point. Formats for all data transfers have been selected for ease of computer input and output and for convenience formatting on the teletypewriter printout. The selected special control characters are unobtrusive, but available if needed.

There is one DPDT relay in the special interface module which is controlled by command from the system control module. The function of the relay is to reverse the direction of current through the test specimen. The relay contacts are used to control toggle and latch relays that control specimen current.

### 5.9 Control Program

The right half of Fig. 10 shows the details of the control module and its program, and the remaining modules with their control connections are shown on the left. Control program steps are indicated by rectangles. Each rectangle is divided into three parts: the right-hand part indicates the number of the step, the upper left-hand part indicates the "do" commands which are energized, and the lower left-hand part indicates the selected conditions to be tested. Transitions between steps are indicated by lines which emanate from bottom corners of each step rectangle, indicating the two transitions which are possible from the step.

In the quiescent state of the system, the controller is in a "wait" loop consisting of step 0 and step 10. Step 0 checks for the presence of a "Read All Data" code and step 10 checks for the presence of a "Read Temperature Only" code.

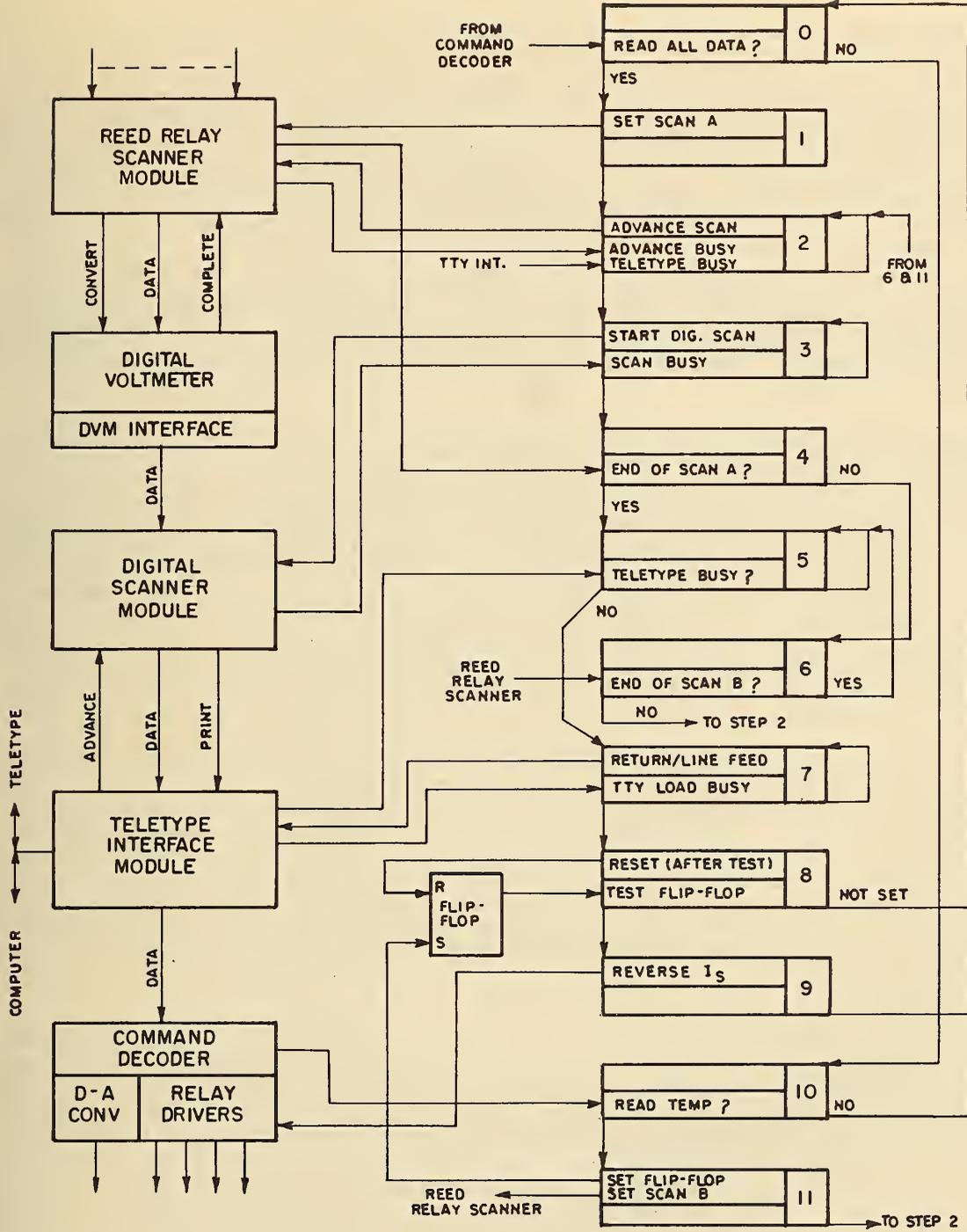


Figure 10. CONTROL MODULE PROGRAM

Assume that a "Read All Data" code is received. The program goes from step 0 to step 1 where a command is issued to the reed relay scanner to put it in the SCAN A mode. Step 1 is followed by step 2 which sends an ADVANCE command to the scanner, causing it to sample the first channel in the SCAN A sequence. The scanner responds with a busy signal which will remain until the digital voltmeter has measured the voltage on this first input. Another condition line to step 2 checks the status of the teletypewriter. The presence of a busy signal on either condition line causes a temporary halt condition because the program goes from step 2 back to step 2. When the voltmeter has finished its task, and if the teletypewriter is not busy, the program advances to step 3, which starts the cycle of the digital scanner module. Again, there is a temporary halt while this scanner is busy. The digital scanner switches the data from the digital voltmeter to the teletypewriter interface module one character at a time. The control signals which cause the digital scanner to advance and the teletypewriter interface to load and transmit are not generated by the control module in this case. Instead, there is interaction of busy signals between the scanner and the teletypewriter interface which causes the process to proceed at its own pace without supervisory control.

When the digital scanner has completed transmission of the last digit of a measurement to the teletypewriter interface, the program proceeds to step 4 where it checks to see if the last channel of the SCAN A sequence has been reached; if not, step 4 is followed by step 6 which is a similar step for SCAN B. Since SCAN B has not been set (we are still doing SCAN A), the program will branch back to step 2 which will advance the reed relay scanner to the next channel. This loop, steps 2, 3, 4 and 6, will be repeated until the last channel of SCAN A has been measured, then the program will go from step 4 to step 5, where it waits for the teletypewriter to finish printing, then on to step 7. Step 7 sends a CARRIAGE RETURN/LINE FEED command to the teletypewriter interface module and waits for that command to be accepted before proceeding to step 8. Step 8 checks a control flip-flop, the significance of which will be explained in the next paragraph. For the case under discussion, step 8 will be followed by step 9 where the current through the Hall specimen is reversed. From step 9 the program returns to the quiescent "wait" loop, step 0 and step 10.

Now consider the case where a "Read Temperature Only" code is detected. This time the program leaves the "wait" loop by going from step 10 to step 11. Step 11 sets the reed relay scanner to the SCAN B mode and sets a control flip-flop so that the controller will "remember" that this is a SCAN B operation. From step 11 the program goes to step 2 and through the rest of the program in the same manner as it did for SCAN A. It will branch out of the 2-3-4-6 loop from step 6 into step 5 when SCAN B is finished. The one major difference in this sequence is the branch that is made in step 8. This is the step that tests the flip-flop set in step 11 and causes the specimen current direction not to be changed after this type of scan. Therefore, the program branches back to the quiescent "wait" loop without going to step 9.

#### 5.10 Assembly of the Interface System

Most of the engineering effort for the Hall effect experiment went into planning the system configuration and the design of circuits for the special interface module for the Hall effect experiment. Before interconnecting the modules, they were tested on the bench as individual units. Since each of the general purpose modules has its own power supply and manual controls, the testing can be quite thorough, yet complex test jigs are not needed. Only simple tests could be performed on the special interface module this way because of its unique relationship to the experiment. The next step was to mount the modules in a rack and interconnect them. Some of the interface system programming was done at this point because selection of cable connections and rear panel patching is part of the programming process. The control module was initially programmed by inserting pins in a matrix plugboard; when the system had been completely installed and tested, the program was wired on printed circuit cards which were inserted into the module, replacing the matrix plugboard.

The assembled system underwent more tests before it was connected to the experiment. During these, the teletypewriter was used to generate the command characters which normally would come from the computer. The same testing method was used again after the system was connected to the experiment. The connection to the computer was the final step in the process; from this point on, further testing depended on the computer system, including the special software developed for the Hall effect experiment.

## 6. SOFTWARE DESIGN

### 6.1 Over-all Software Design

The software directly supporting the Hall effect experiment consists of a user program written in CAS Assembly Language that runs in the user processor of the time-shared system during the time slices allocated to the experiment. The program uses system commands for input and output and for conversion from character input to floating point internal form. It also uses the floating point software package that is an integral part of the user processor supervisor.

Figure 11 shows the general program flow for a run of the Hall effect experiment. The parameters for the run include the specimen geometry and a set of stop points for thermocouple voltage representing temperature values. The specimen is brought to the temperature corresponding to the first stop point and a full set of data is taken from the experiment. During the data input sequence the heater current, which controls specimen temperature, is adjusted to minimize temperature drift.

The magnetic field, resistivity, Hall coefficient, and Hall mobility are then computed for this stop point. These results are printed on the local teletypewriter, and, if the operator has specified storage of raw data all of the input data are stored on magnetic tape. If there are additional stop points, the control program is set for the next one and the temperature control cycle begins again. When the last stop point has been reached, the program halts after printing an appropriate message on the teletypewriter.

### 6.2 List of Symbols

$a_{c,i}$	heater current calculation parameter
$b_{c,i}$	heater unit calculation parameter
CONTROL	numerical value of one of the characters [!, ", \$, %, (] used to control
CHAR.	experiment
$d_1$	distance between specimen arms 4 and 6
$d_2$	distance between specimen arms 3 and 5
$D_p$	$p^{\text{th}}$ set of stored data (see Table 3)
F	magnetic tape file name
HCC	heater control character
i	index
$I_H$	heater current (mA)
IHP	Hall generator current
$IHP_i$	IHP of $i^{\text{th}}$ stored data set (same for VHP, VSR, V46,...)
k	index on stop points ( $1 \leq k \leq n$ , n number of stop points)
L	magnetic field off flag
$MTV_{c,i}$	maximum thermocouple voltage as a function of coolant (c) and temperature range (i)
OUT	save flag (0 or 1)
p	index on data sets
$R_H$	Hall coefficient calculated from voltages measured between specimen arms 5 and 6
$R_H'$	Hall coefficient calculated from voltages measured between specimen arms 3 and 4
$R_{Hav}$	average Hall coefficient
RN	record number of file F
$R_S$	standard resistor (used for measuring specimen current)
$t_s$	specimen thickness
VHP	Hall generator voltage
$V_I$	inside thermocouple voltage
$V_{Iav}$	average inside thermocouple voltage
$V_k$	$k^{\text{th}}$ stop point voltage
$V_O$	outside thermocouple voltage
VSR	voltage across standard resistor (specimen current)
V35	resistivity voltage (see Fig. 5)
V46	resistivity voltage (see Fig. 5)
V34	Hall voltage (see Fig. 5)
V56	Hall voltage (see Fig. 5)
$w_S$	specimen width

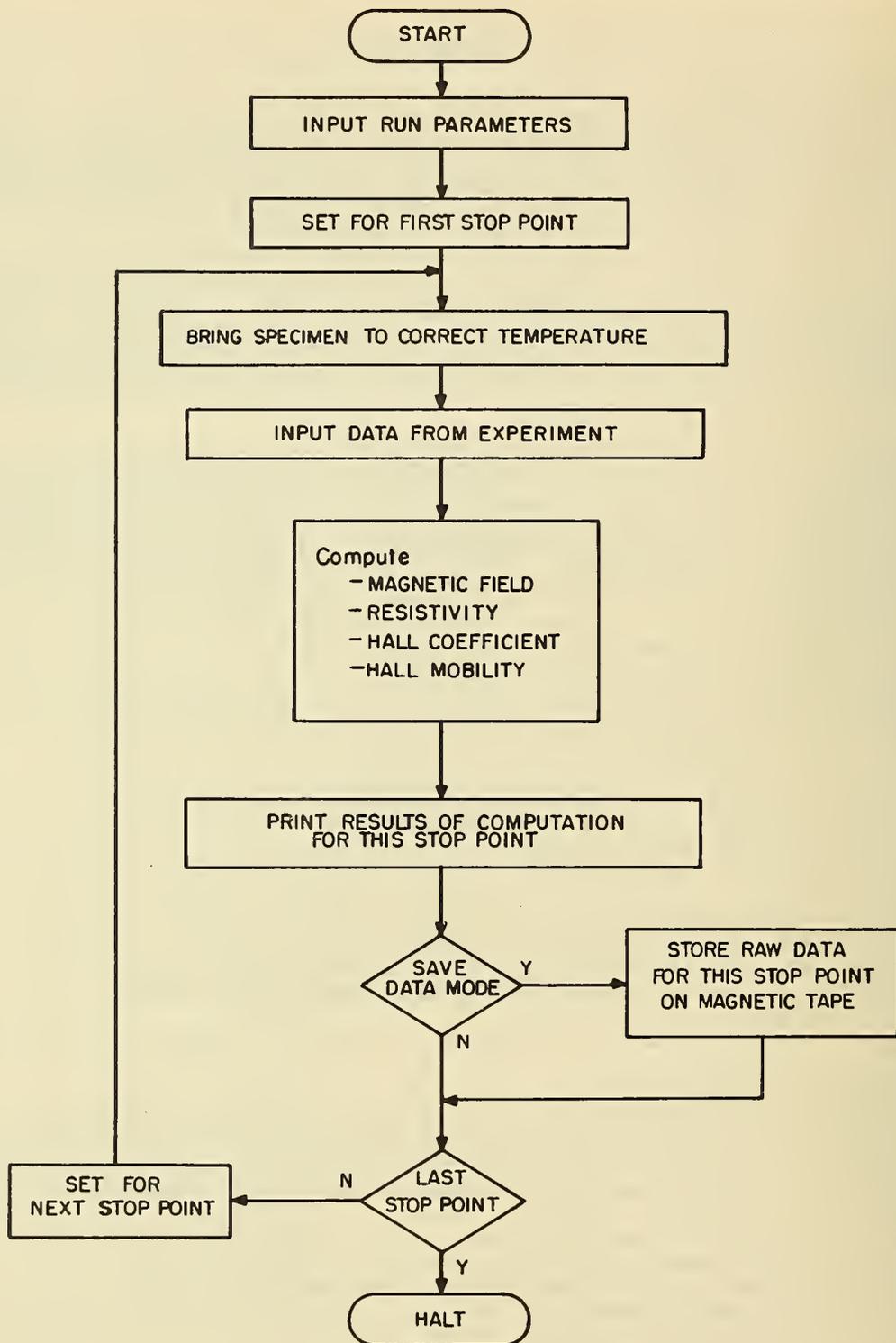


Figure 11. GENERAL PROGRAM FLOW

i \ c	0	1
0	-10.45	-12.90
1	- 9.44	-12.45
2	- 6.68	-11.40
3	- 3.71	-10.00
4	-	-

c =  $\begin{cases} 0, \text{LN}_2 \text{ coolant} \\ 1, \text{LHe coolant} \end{cases}$

i = temperature range index

(all voltages in mV)

Table 1. MAXIMUM THERMOCOUPLE VOLTAGES (MTV) FOR EACH TEMPERATURE RANGE AS A FUNCTION OF COOLANT

a:

i \ c	0	1
0	0.56050	0.1060
1	0.2600	0.1060
2	0.2172	0.1160
3	0.1954	0.1260
4	0.1954	0.1360

b:

i \ c	0	1
0	0.04770	0.0059
1	0.01710	0.0059
2	0.01000	0.0059
3	0.00674	0.0059
4	0.00526	0.0059

c =  $\begin{cases} 0, \text{LN}_2 \text{ coolant} \\ 1, \text{LHe coolant} \end{cases}$

i = temperature range index

Table 2. HEATER CURRENT PARAMETERS a and b AS A FUNCTION OF COOLANT AND TEMPERATURE RANGE

$\mu_H$	Hall mobility
$\rho_A$	resistivity calculated from voltages measured between specimen arms 4 and 6
$\rho_B$	resistivity calculated from voltages measured between specimen arms 3 and 5
$\rho_{av}$	average resistivity

### 6.3 Subroutines

Full understanding of the detailed program description in the next section requires a description of two basic subroutines. They are:

- (a) WAIT (n). This routine uses the system clock to delay n seconds before continuing the program.
- (b) CALCUR (m,n). Given m, the present thermocouple voltage, and n, the desired thermocouple voltage, the heater current necessary to approach or maintain the desired thermocouple voltage is calculated. This value is converted into the appropriate character code and is transmitted to the experiment.

Details of the heater current calculation subroutine are shown in Fig. 12. The primary entrance, CALCUR (m,n), requires as input the present and desired thermocouple voltages. An alternate input, CALCUR' (n), requires only the desired thermocouple voltage. The routine then reads the temperature data directly from the experiment and uses this to set m.

There are two thermocouples, either of which may be used for the value of m in calling CALCUR. These are labeled  $V_I$  and  $V_O$ , for inside and outside thermocouples. The inner one is located near the specimen and the outer one is external to the specimen holder, but near the heater. In general, equilibrium at a stop point is reached when the inner thermocouple is within 15  $\mu V$  of the desired value and the difference between the inner and outer thermocouple values is less than 40  $\mu V$ .

For the CALCUR' program entrance the desired temperature data is read by transmitting the [%] control character to the experiment and then executing a character string input command. The values of  $V_I$  and  $V_O$  are transmitted back to the computer and this transmission is terminated with a carriage return character. The carriage return causes termination of the input command executed by the program.  $V_I$  is then converted into internal floating point form and stored in m.

The contents of m is next compared to the maximum thermocouple voltage for each of four temperature ranges. Table 1 shows these maxima, where i, the index on the ranges, varies from 0 to 4. There are separate sets of ranges, one for liquid helium and one for liquid nitrogen coolant. All thermocouple voltages algebraically greater than -3.71 or -10.00, depending on range, are in range 4. This table was derived by examination of the plot of thermocouple voltage as a function of temperature. A set of straight lines that approximate the curve in five different regions were identified graphically. The table values are the maximum thermocouple voltages for each temperature range as a function of coolant.

The computation of heater current,  $I_H$ , is based on present and desired thermocouple voltages. This computation uses a set of empirically determined coefficients which depend on voltage range and coolant (see Table 2). The first term,  $a_{c,i}$ , introduces a constant current for each temperature range. The second term,  $n \cdot b_{c,i}$ , subtracts a correction for the specific thermocouple voltage desired within that range. At equilibrium, the current specified by these two terms should balance the effect of cooling by effluent gas and hold the temperature constant. The contribution of the third term is proportional to the difference between present and desired temperature. This term is especially significant when moving from one stop point to the next since it adds a varying amount to the heater current, thereby bringing the specimen holder to the desired temperature quickly, but with little overshoot. The term is also important to compensate for drift during the data input sequence.

During system design several approaches for temperature control were suggested. The initial one was simply to output a control character which initiates a fixed length pulse to the heater. Since the effective heat added to the specimen is a function of the integral of heater current over a period of time, varying the pulse frequency would provide limited temperature control. It was found that the constantly varying heater current disturbed measurements being made on the Hall effect specimen. It was also found that drift during data input was too great and, therefore, a more sophisticated controller was required.

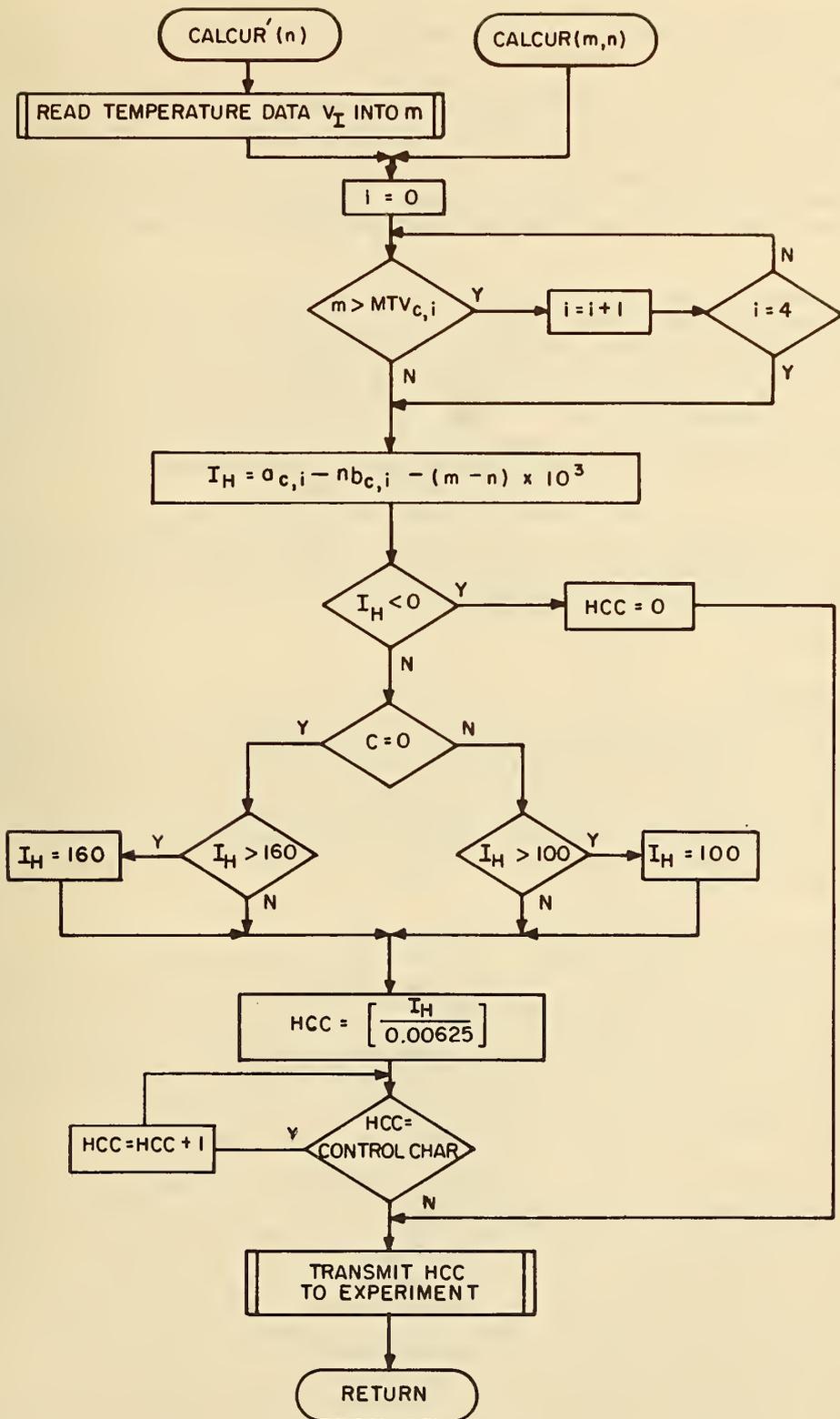


Figure 12. HEATER CURRENT CALCULATION SUBROUTINE

Hardware was then implemented to allow 256 increments of heater current as specified by a single 8-bit ASCII character from the computer system. This control mechanism was first used with the first two terms of the equation for  $I_H$  shown in the flowchart; however, the time required to reach each stop point was much longer than was considered acceptable. Drift during the data input sequence was also unacceptable. The third term in the equation was added and its coefficient was adjusted empirically so that the time required to move between stop points is acceptable, yet the overshoot introduced by the thermal inertia of the specimen and its environment can easily be corrected and the temperature brought to equilibrium for the data input sequence. Additional sophistication, such as the addition of a second order derivative term, was not found necessary for successful operation of the experiment.

If  $I_H$  is negative, then HCC, the heater control character, is set equal to 0. If  $c = 0$  (coolant is liquid nitrogen), then a maximum heater current of 160 mA is allowed. If the coolant is helium, the maximum is 100 mA. The heater current is then translated to an HCC value of from 0 to 256. HCC is the numerical code of the character to be transmitted to the experiment. HCC is then compared with the list of control characters. If HCC is a control character, it is incremented by one unit and then checked again. This check is necessary since the hardware interface at the experiment does not turn off its control character detection circuit while it is receiving the heater control character.

Finally, HCC is transmitted to the experiment in the following manner. First, the character  $[ ( ]$  is transmitted to the interface, this indicates that the next character transmitted is the heater control character. HCC is then transmitted and the interface sets the new heater current and holds it constant until the next HCC value is received.

## 6.4 Program Details

### 6.4.1 Initialization

As shown in Fig. 13, the thermocouple stop points  $V_1, V_2, \dots, V_n$  are first entered by the operator of the experiment using the local teletypewriter. Conversational parameter entry continues with input of the value of the standard resistor,  $R_s$ , used to compute specimen current, followed by input of specimen geometry: specimen width and thickness and distances between contacts. Entry of the coolant type, LHe or LN<sub>2</sub> is followed by a query for setting the data save mode. If the raw data is to be saved, the tape file record number is set to 1 and the tape file name is entered by the operator and stored in F. The index stop point index, k, is set equal to 1.

### 6.4.2 Temperature Check and Set Up for Data Input

Temperature data is read from the experiment in a manner identical to that described for CALCUR'. Figure 14 shows that the absolute magnitude of the inside thermocouple voltage is compared to the desired stop point voltage. If this difference is less than 15  $\mu$ V the magnitude of the difference between inside and outside thermocouple voltages is then checked. If this difference is less than 40  $\mu$ V, adequate stability has been achieved at the new stop point and the program continues. If either test fails, CALCUR is called using the outer thermocouple voltage; then a delay of five seconds is introduced to wait for this heater current change to take effect and the temperature is again checked.

Figure 15 details the remainder of initialization and the beginning of the data input sequence. Flag L, used to initiate signalling the operator if the magnetic field is manually turned off, is first set to 0. CALCUR is called, this time using the inside thermocouple voltage  $V_I$ . The field is then turned on using the  $[ " ]$  control character. A delay of 12 s is triggered by a  $[ \$ ]$  control character and results in input of  $V_I$ , inside thermocouple voltage, VHP and IHP, for Hall generator voltage and current (used for measuring magnetic field), and VSR, voltage across the standard resistor used to measure specimen current. Four voltages across terminals on the specimen are also measured. The absolute magnitude of the Hall generator voltage is next checked to determine if the field is actually on. If the magnitude of VHP is not greater than 5 mV, Flag L is set to 1 and the loop continues with another call to CALCUR. Every time this loop is re-entered when Flag L equals 1 a message is printed on the teletypewriter and a 5 s delay is introduced to allow the operator to turn on the magnetic field manually.

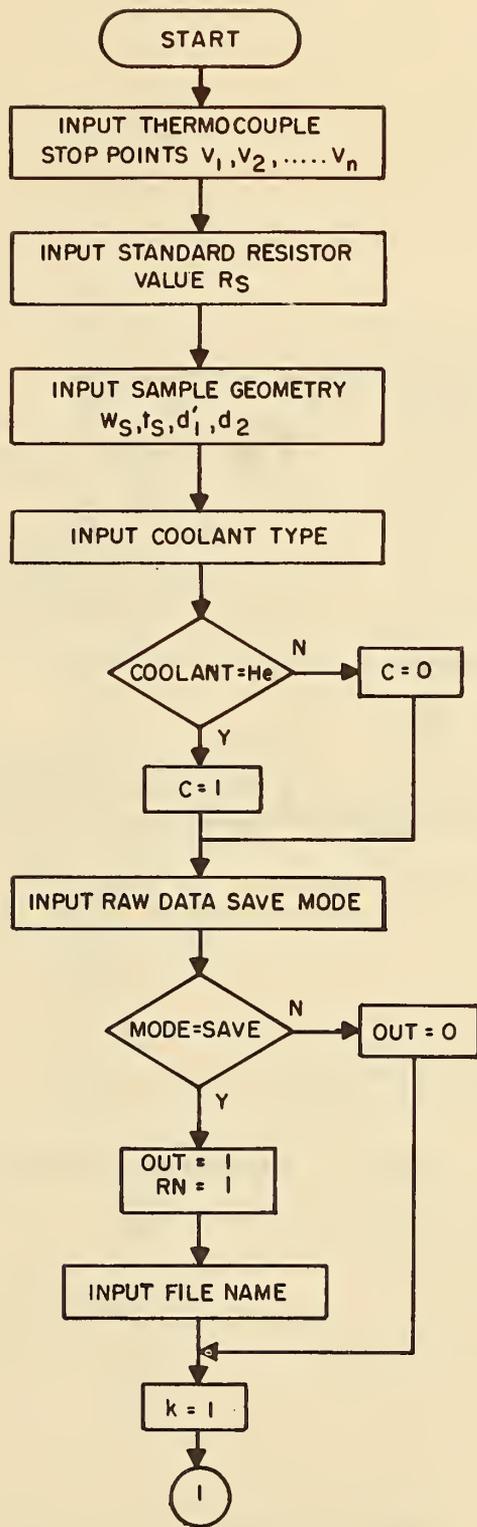


Figure 13. INITIALIZATION

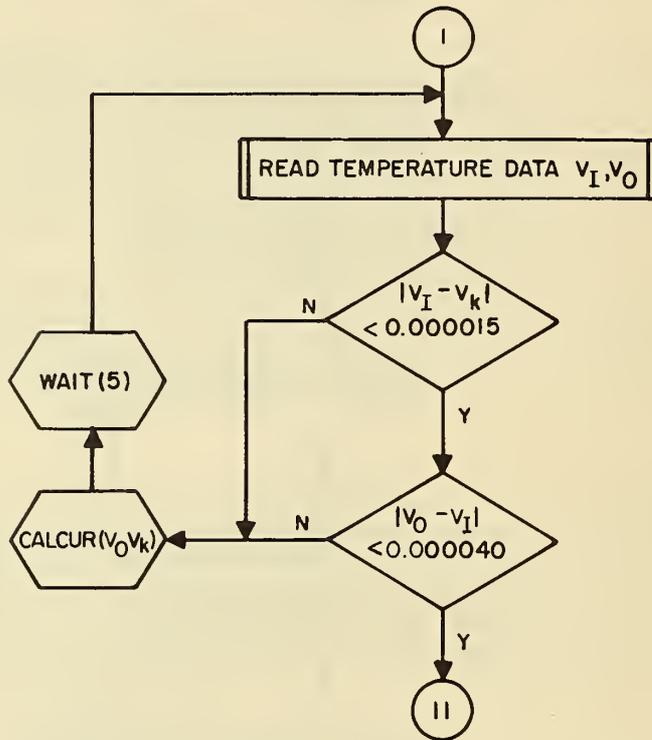


Figure 14. TEMPERATURE STABILITY CHECK

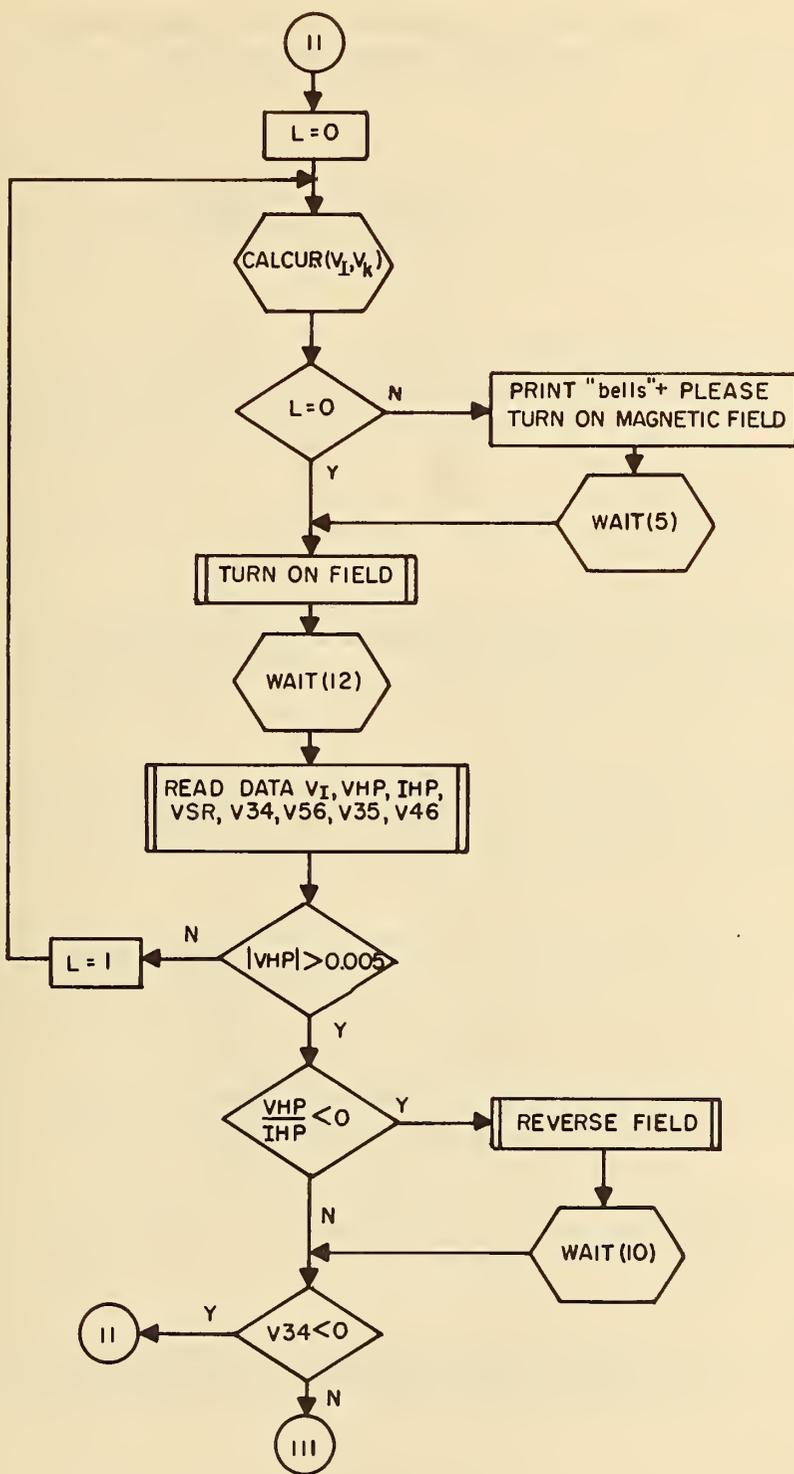


Figure 15. INITIALIZE FIELD AND SPECIMEN CURRENT

EACH DATA SET,  $D_p$ , CONSISTS OF A SET OF DATA VALUES:

$V_I, V_{HP}, I_{HP}, V_{SR}, V_{35}, V_{46}, V_{34}, V_{56}$

P	FIELD	CURRENT
1	+	+
2	+	-
3	-	+
4	-	-
5	0	+
6	0	-

Table 3. ORGANIZATION OF STORED DATA

i	e	f
1	111930	294
2	111930	294
3	111800	285
4	111800	285

Table 4. FIELD COMPUTATION COEFFICIENTS

If the magnitude of VHP exceeds 5 mV, the direction of the field is checked. When VHP divided by IHP is less than 0, the field is negative with respect to an arbitrary convention and must be reversed. Reversal is achieved with the [!] control character and is followed by a delay of 10 s to allow the field to stabilize. At this point, if V34 is less than 0, the specimen current is not positive with respect to an arbitrary convention and the program returns to point II. Note that every use of [\$], the read data control character, reverses the specimen current; therefore, the next time the test for current direction is reached V34 will be greater than or equal to 0, indicating a positive current. Once the field is on and in a positive direction and the current is in a positive direction, the data input sequence begins.

#### 6.4.3 Data Input

The first data set, for positive field and positive current, has been read during the initialization cycle. Figure 16 begins with storage of this data set with label  $D_1$ . Table 3 outlines storage of the six data sets taken during a run. These sets are indexed by the variable p and consist of all combinations of positive, negative, and zero fields with positive and negative specimen current.

CALCUR' which inputs, computes, and transmits the drift-compensating heater current is then called. After a delay of 5 s for this change to take effect, a new data set is taken and stored as set  $D_2$ .

After field reversal, a delay is necessary to wait for the field to stabilize. During this delay, two calls on CALCUR' are made to minimize temperature drift and then data set  $D_3$  is read and stored. Note that data set  $D_3$  is for positive specimen current. Following input of  $D_3$ , however, specimen current is negative and, following another CALCUR' and a delay of five seconds, data is read and stored as data set  $D_4$ .

The program continues in Fig. 17 with reversal of field in preparation for the next run followed by a delay which includes a call to CALCUR'. The field is then turned off and the following delay also includes a call to CALCUR'. Data is read and stored as data set  $D_5$  and a final call to CALCUR' and a delay of five seconds precedes the input and storage of the last data set,  $D_6$ .

#### 6.4.4 Calculations and Completion of Run

The magnetic flux density is computed from the Hall generator voltage and current for each of the first four data sets. Figure 18 shows this computation and Table 4 lists the coefficients used in field computation.

Two resistivities  $\rho_A$  and  $\rho_B$  are computed as shown in the flowchart, the Hall coefficients  $R_H$  and  $R_H'$  are computed by the formulas shown in the flowchart, and these are averaged to compute  $R_{Hav}$ . The four magnetic field values are averaged and the Hall mobility and average thermocouple voltage during data input are computed.

Figure 19 shows the printing on the teletypewriter of the various computed values. If the output flag OUT has been set to 1, all six data sets are stored in record PN of file F, the record number is increased, and a "data save" message printed. Otherwise a "data not saved" message is printed.

If there are additional stop points, the program continues at point I. When the last stop point, n is reached, an HCC of 0 is transmitted to turn the heater current off, and "run completed" is printed on the teletypewriter. The program then halts.

## 7. SYSTEM OPERATION

### 7.1 Experimental Procedure

The first step in preparing for each run was to transfer liquid helium into the pre-cooled Dewar flask. For a morning run the cryostat was pre-cooled with liquid nitrogen overnight. During the helium transfer it was helpful to read the voltages of the thermocouples attached to the specimen holder to see how the transfer was progressing. This could be done on the local mode by typing the [%] control character on the teletypewriter. Usually the transfer was stopped when the helium level reached the specimen holder as the first data

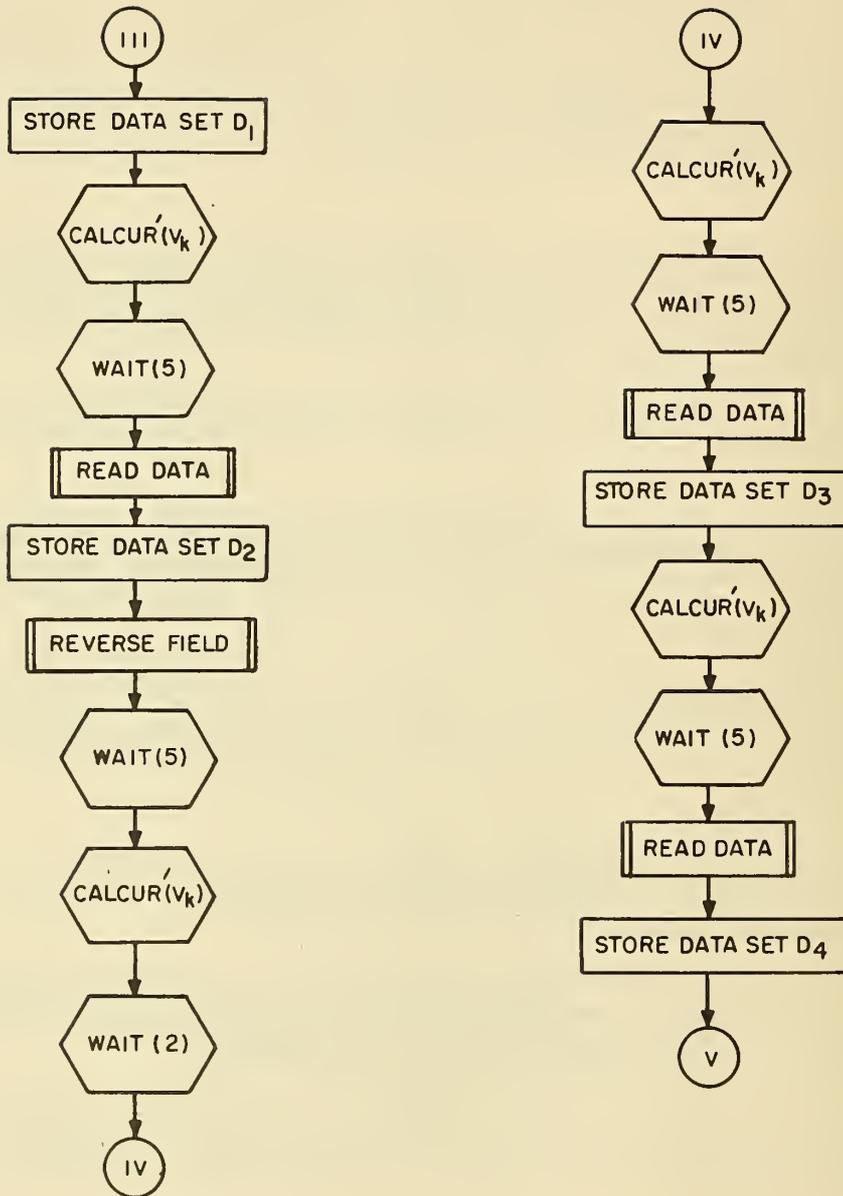


Figure 16. DATA INPUT

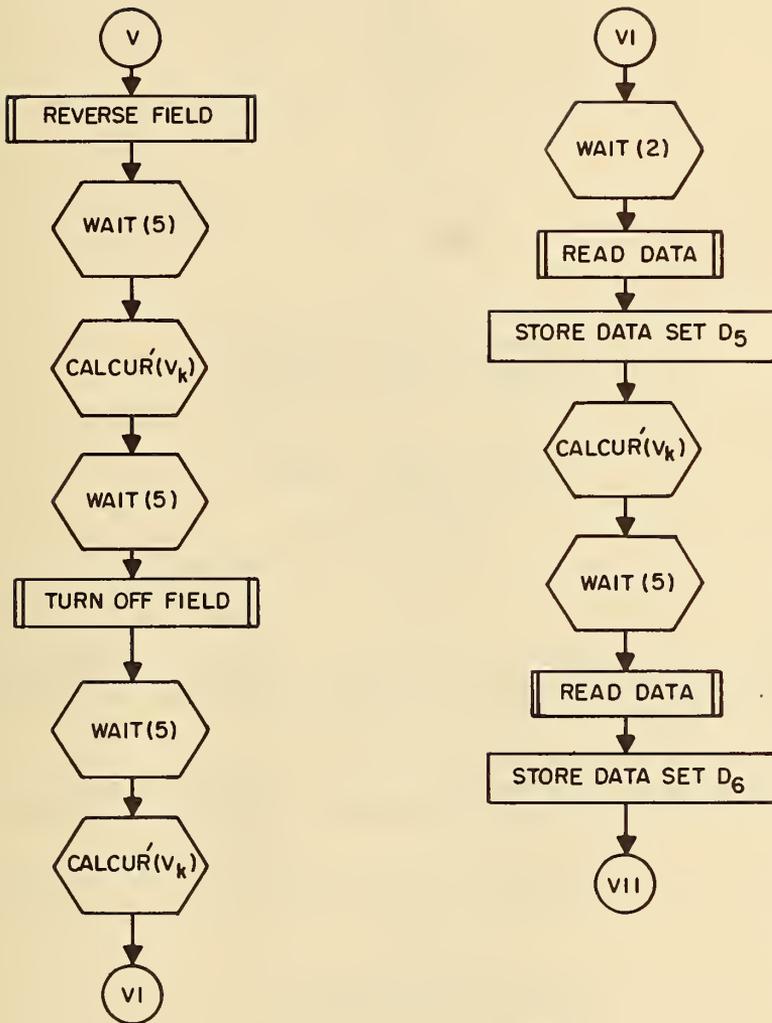


Figure 17. DATA INPUT

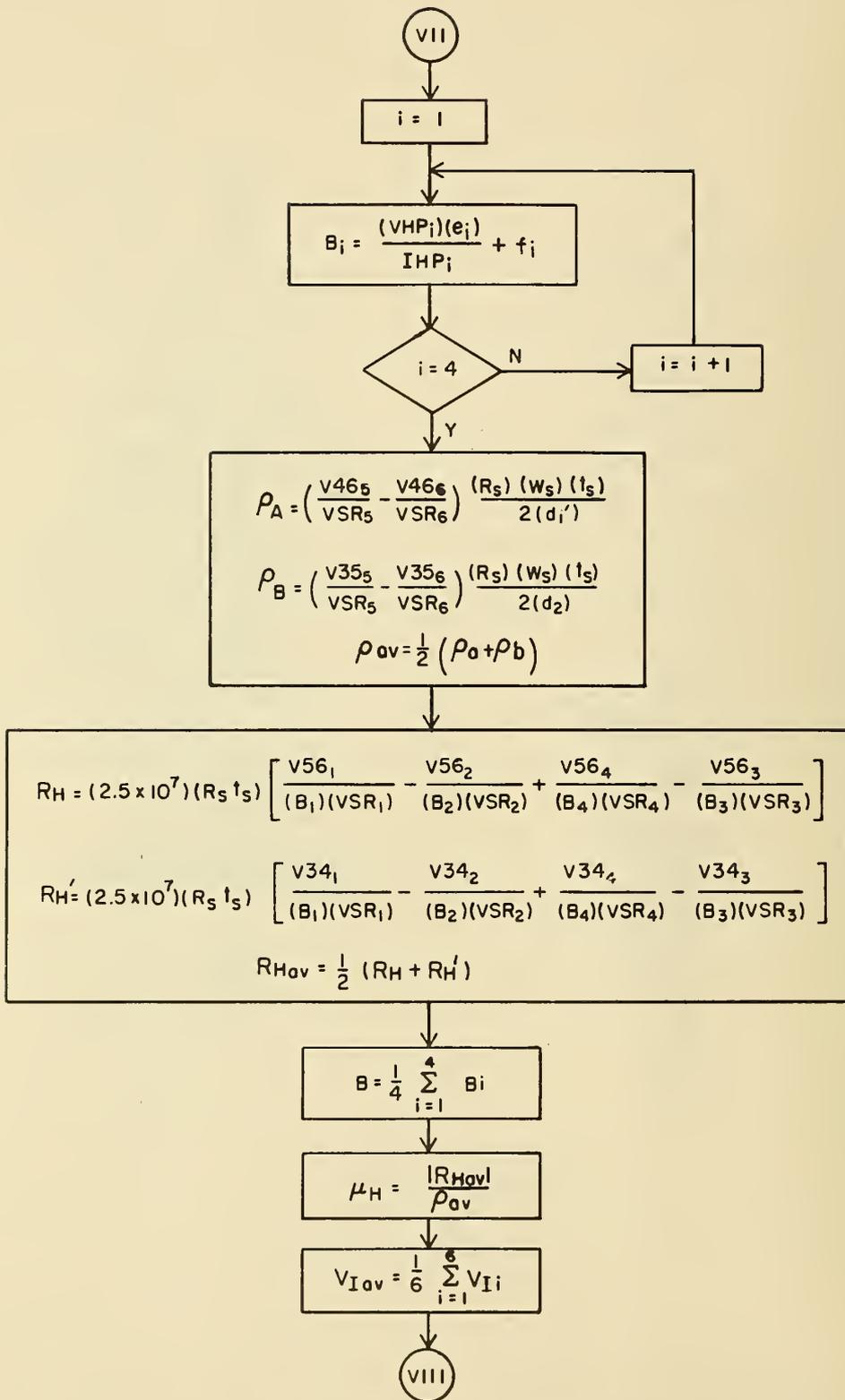


Figure 18. CALCULATION OF FIELD, RESISTIVITY, HALL COEFFICIENT, HALL MOBILITY, AND AVERAGE THERMOCOUPLE VOLTAGE

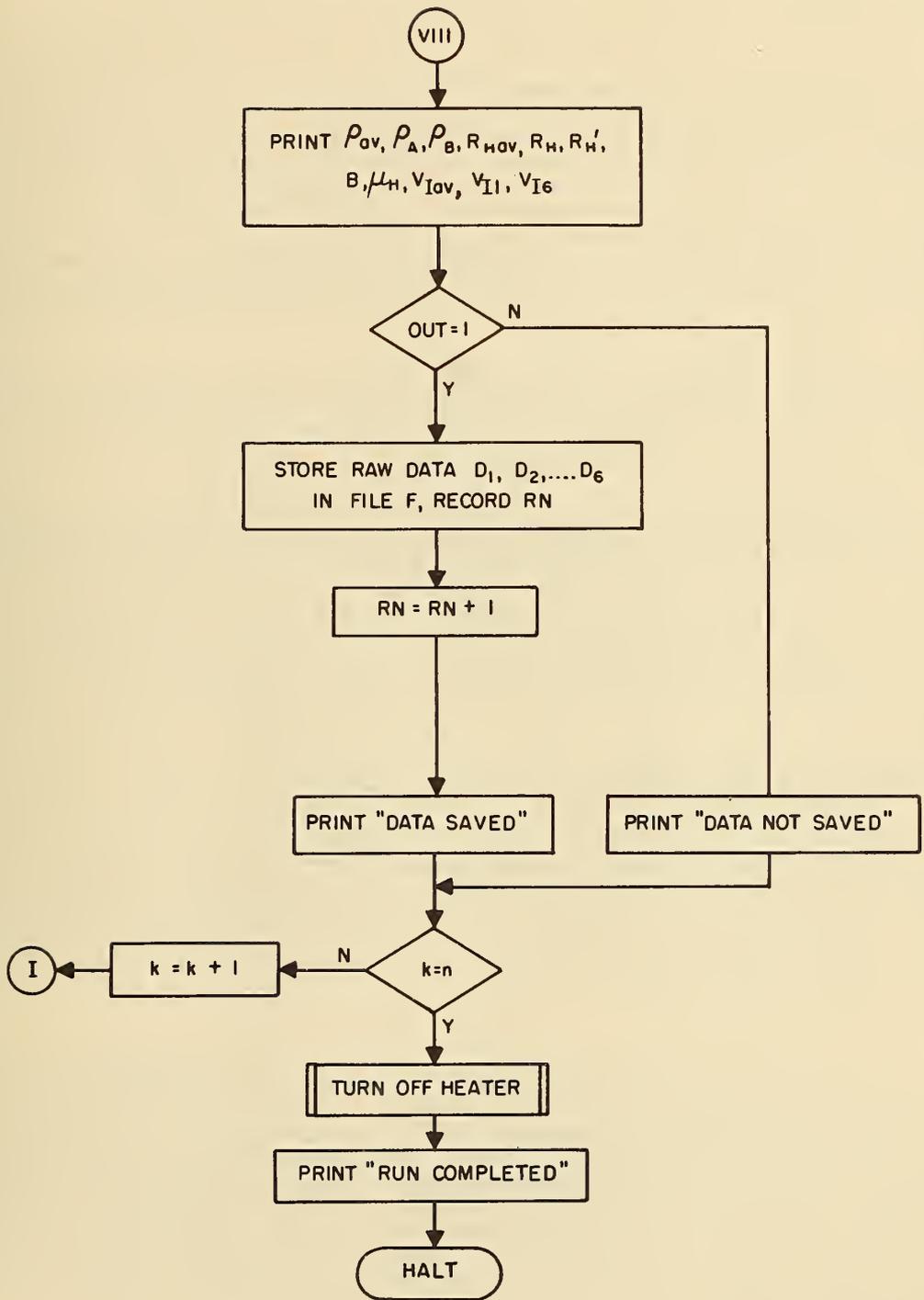


Figure 19. PRINT RESULTS OF CALCULATIONS, SAVE DATA, AND CHECK FOR COMPLETION

point desired was about 15 K. Sometimes helium was transferred above the holder so a calibration check at 4.2 K could be made on the thermocouples.

Next, the specimen current was turned on and adjusted to the desired value. The magnitude was that necessary for an electric field of 0.01 to 1 V/cm in the specimen. Readjustment was often necessary when the temperature for the first data point was reached. A standard resistor was chosen which gave a voltage reading of at least three significant figures for VSR. The standard resistor could usually be kept at some fixed value, but if the current was very small, a larger resistor than normal was needed. If the resistor was changed during the run, it was inconvenient to stop the data taking to type in the new value since all of the information called for must be reentered, so the output affected was just scaled by the appropriate power of ten. At low temperatures it is important to keep the voltage across the specimen small in order to avoid hot-carrier effects. If the specimen resistance changed significantly during the run, the current was adjusted manually to maintain sensitivity and avoid heating.

As a check, specimen data were obtained in a local mode of operation by entering the appropriate control characters on the teletypewriter. Of course there was no computation, but from the values of the voltages which were printed on the teletypewriter it was possible to determine that the experiment was operating satisfactorily.

Time-sharing operation began by switching to the computer mode, logging in, typing in the thermocouple voltages corresponding to the temperatures desired, and answering the questions posed by the computer concerning the standard resistor, specimen dimensions, and coolant type. Normally about 20 data points were taken with liquid helium as the coolant. This usually required 1-1/2 hours. Sometimes it was desirable to repeat a point because of a poor choice of specimen current, temperature fluctuations, or other reasons. This could be done before the intermediate output was printed by striking the abort key on the teletypewriter and then typing the appropriate command. To repeat the point at a later time involved reentering that thermocouple voltage along with any others remaining to be done and answering the questions again. Since the sample dimensions do not change, it would have been more convenient to answer these questions before typing in the voltages and then have an alternate entry in the program after these questions.

Several times measurements were made above 200 K with good temperature control using helium as the coolant. However the usual procedure was to boil away the liquid helium rapidly with warm helium gas and then fill the inner Dewar flask with liquid nitrogen. The next set of thermocouple voltages was entered with at least one point overlapping the helium set. It took about 15 min to switch coolants and resume data collection. About 2 hours were needed to obtain 18 data points from 80 K to near room temperature. For example, it took 5 min to change temperature from 125 K to 135 K and 2 min to obtain the data and print the intermediate output.

It was desirable to have an operator in the room with the equipment so that any difficulties could be quickly remedied. Sometimes an error occurred which stopped the computer control of the experiment. A message was automatically typed, following which the operator must respond with a command in order to restart the operation. In other situations computer personnel had to be notified of terminal troubles, as the run was usually not monitored at the computer. Also there were occasions when the specimen holder would not reach the stop point temperature. It was possible for the operator to increase the current through the heater by entering certain control characters on the teletypewriter. In instances where the temperature stabilized above the stop point, the heater power supply could be turned off to cool the specimen so that another approach could be made to the point. The operator had 2 to 3 hours during the run that he could use for other activities, such as plotting data from previous runs.

## 7.2 Limitations of the System

The 1 G $\Omega$  input impedance of the digital voltmeter limited the measurements to source resistances of less than 10 M $\Omega$  for loading error of less than 1 per cent. Specimen contact resistance must be included when determining the loading effect. Since the calculations involve ratios of voltage, it is possible to reduce the error by selecting a standard resistor which is about the same as the source resistance. By using an electrometer in front of the digital voltmeter, measurements can be made on specimens whose resistance exceeds the input impedance of the digital voltmeter [11].

Acceptable data could be obtained at temperatures above 20 K. Below that three factors limited the accuracy of the results. First, the thermocouple voltage could only be read to four significant figures by the voltmeter. Second, the sensitivity of the thermocouples is less than at higher temperatures. Last, below 20 K the specimen holder responded very quickly to a change in the heater power, and temperature fluctuations in phase with the control corrections resulted unless the power was almost exactly right for that temperature. Finer steps in the power and a shorter time between adjustments would have helped, but in view of the other limitations it was hardly worthwhile to refine the control.

### 7.3 Results

More than 20 measurement runs were made on germanium and 10 on indium antimonide specimens during a period of 4 months. It was possible to measure a specimen each day, since less than 2 hours were needed to put another one in the holder.

The print out of the calculated values immediately after the measurement sequence was a very useful feature. One could see at a glance if the results were reasonable and, if not, take corrective action in time for the next point. Since the quantities were available for plotting immediately, trends could be followed as the run progressed.

Reproducibility of the data obtained by computer-controlled operation was checked at 77 K by repeating the point many times. In each instance the values were the same to four significant figures. The computer results were in good agreement with those obtained manually. A partial run was made on the specimen for which manual data was available and the resistivities agreed within 1 per cent and the Hall coefficients within 2 per cent.

The thermocouple was read only to the nearest 10  $\mu\text{V}$  with a possible 2 digit or 20  $\mu\text{V}$  error. This gives a possible uncertainty of  $\pm 1$  K at 20 K decreasing to  $\pm 0.5$  K above 100 K. However, whenever the digital voltmeter reading was checked with a more sensitive potentiometer, the two values always agreed within  $\pm 10$   $\mu\text{V}$ . So the uncertainty in temperature due to the voltmeter reading is no more than  $\pm 0.2$  K above 100 K.

Temperature stability during the taking of a data set was usually such that the spread of the six thermocouple readings did not exceed 20  $\mu\text{V}$  and was frequently less. The voltmeter was not sensitive enough for a detailed evaluation of the computer temperature control, but above 20 K the control was satisfactory. Another indication of good temperature equilibrium in the specimen holder was the absence of significant offset in the results from the two coolants in the overlapping temperature range. Typically differences of less than 2 per cent were found. The temperature control might have been even better had more sensitive thermocouple readings been available.

## 8. SYSTEM EVALUATION

### 8.1 Influence of the Computer on the Experiment

It is interesting to compare this data acquisition system with other methods of obtaining data from the Hall effect experiment. Previous experience with manual measurements showed that at least 3 days were required to take 40 points by the d-c method using a potentiometer. This can be shortened to 2 days if the Dauphinee method [12] is used. This technique utilizes a chopper which reverses the specimen current and thereby relieves the operator of this task. Manual measurements are tedious and mentally fatiguing, so usually only a minimum number of points are taken. The conclusions drawn from limited data may not be as certain as those from a larger number of points.

About 2 days are needed to calculate 40 points either with a slide rule or mechanical calculator. This time can be reduced to less than one day if a programmable, electronic calculator is available. Thus from 24 to 40 man hours are needed to take data and make calculations that can be completed by the computer system in 4 hours.

Several other automatic data collection systems have been used to make Hall effect measurements [11, 13-15]. These systems, though different in many ways, have the common feature that the temperature is not controlled. Rather, measurements are made as the temperature of the specimen slowly drifts upward or downward. In the present case the temperature drift would be excessive because of the relatively long time (15 s) required for the magnetic

field to become stable after being turned on or reversed. This effect is particularly serious in temperature regions where the Hall or resistivity voltage changes rapidly with temperature.

It should be emphasized that the method of controlling the temperature in the present experiment is not necessarily the best which could be used. Another method, which should be an improvement, especially at low temperatures, involves the use of a standard temperature controller with the set point supplied by the computer. In this case, an electrical signal, sent by the computer, is translated into a temperature set point by a digital-to-set point converter.

In addition to the speed, a second advantage of the computer-controlled system is the computation and print out of the data immediately after each measurement sequence. This feature permits the operator to plot the data during the run and to rerun any portion of the range in which unusual or interesting features are observed. Although rerun of a set of data points was rather inconvenient in the present system, the problems could be solved simply by rearrangement of the input sequence.

Another feature of the system, an option to store the calculated quantities on magnetic tape and then call for a summary print out at the end of the run, was never implemented. This feature would have been very convenient for plotting the results after a run. Arrangements could have been made to plot the data by machine after storing the values on magnetic tape or after punching paper tape during the summary print out on the teletypewriter.

Major disadvantages of the system were the cost and availability of terminal time. Operating cost is estimated at about half that required to obtain the same data by hand. Other types of data acquisition systems, for which the initial investment is about the same as the computer-controlled system, can be operated for about one quarter the cost of manual operation.

Because on-line computer control is not a necessity for the Hall effect experiment, another data acquisition system was recently obtained and installed. Its output is in the form of punched cards which are processed at the NBS computer facility. The various function changes, such as reversal of specimen current and magnetic field, are accomplished by voltage level changes which occur during the data collection cycle. This system uses a standard temperature controller with an operator to adjust the set point or a stepping switch which connects each set-point voltage in succession to the controller. A clock timer is set for a period long enough to insure that thermal equilibrium has occurred before the data cycle is initiated. For this reason it may require 6 hours to obtain the same data the computer system obtained in 4. The operating cost per run, however, is about half that for on-line operation. In addition, runs can be made at any time which is an advantage when there are restrictions on the availability of a computer terminal. It is very inefficient from the user's point of view if the terminal must be released at a certain time before all of the desired data has been obtained.

All data in the off-line system are processed after the run is completed. Therefore, a run may have to be repeated occasionally because of errors or unusual features which could have been detected during the run if calculated values had been available immediately. It is most helpful to have an immediate print out when very little is known about the specimen being measured.

## 8.2 Influence of the Experiment on the Computer

The design objective in attaching the Hall-effect experiment to the time-sharing computer was to limit the load on the computer system to that normally encountered with a teletypewriter terminal used for conversational operation. This objective was met; in fact, the load on the computer system is less than that of a typical time-sharing user.

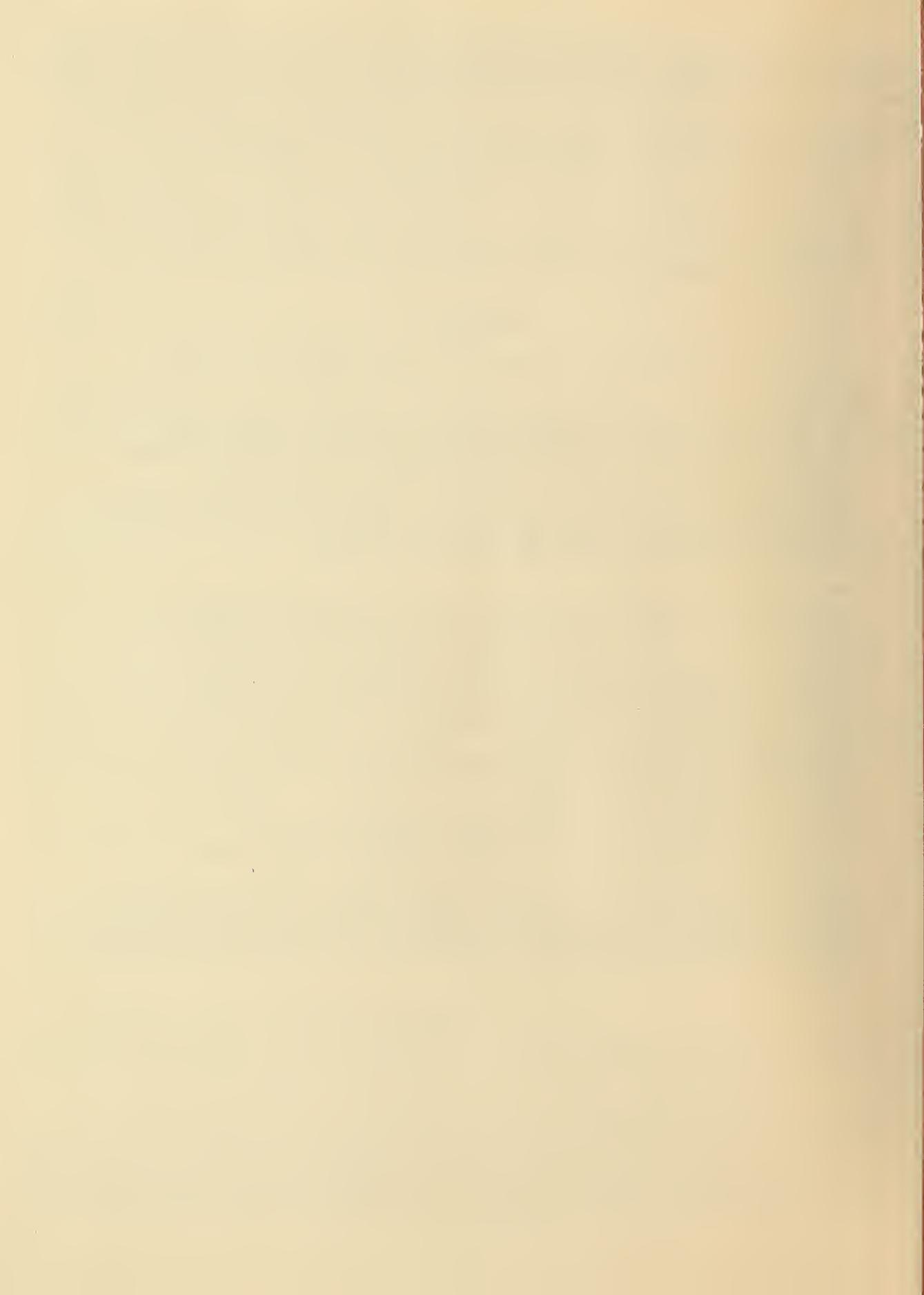
The program associated with the Hall effect experiment is small enough to be retained in the core memory of the particular time-sharing system used, and use of disc or magnetic tape is necessary only for data storage. Although transmission of data to the computer system is at the maximum teletypewriter rate of 10 characters per second, such transmission is made for a small percentage of the time and there are relatively long periods when the program idles waiting for a change in specimen temperature.

Even with such a light load on the computer system, the connection of the experiment to the computer resulted in substantial performance gain, as described above. It is quite possible to attach this or a similar experiment, with respect to computer assistance requirements, to any time-sharing system that meets certain minimum characteristics. One important such characteristic is the ability to input and output arbitrary characters and character strings, either in assembly or a higher level language. Another requirement is that the worst case response time of the system meet the demands of the experiment.

The use of configurations similar to this introduces the possibility of using general-purpose time-sharing systems to support large numbers of on-line experiments. It is interesting to speculate about the possibility of using existing commercial and private time-sharing systems not only for conversational man-system interaction, but in support of special-purpose experimental equipment.

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